AN APPROACH TO DIRECTION FINDING INVOLVING THE PHASE CODING OF THE RECEIVED SIGNAL UTILIZING COMPLEMENTARY SEQUENCES

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THESIS

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by

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An Approach to Direction Finding Involving the Phase Coding of the Received Signal Utilizing Complementary Sequences

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ABSTRACT

Unambiguous accurate direction finding results are obtained by the use of large stationary antenna systems at the lower frequencies and by the use of rotatable antennas at the higher frequencies. While these techniques result in good data they suffer from the fact that accuracy is generally a direct function of the antenna size, that is, accuracy increases as the antenna size increases.

A system is proposed which encodes the outputs of several simple omnidirectional antennas and processes this modified signal to provide angle-of-arrival data. The processor not only provides the angle-of-arrival data but the received signal is preserved as a simultaneous output with the bearing data.

The coding is accomplished utilizing complementary sequences and a derivative of these sequences called orthogonal complementary sequences. The technique is described in detail and a digital computer model was developed to support the theory.

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I. INTRODUCTION

The fundamental method for determining the location of a radio frequency (RF) emitter lies in defining a set of independent curves in the required two or three dimensional space with each curve containing the emitter location as one of the sets of points of the curves. The intersection of these curves will locate the emitter.

The function of a direction finding (DF) system is to determine the unambiguous direction-of-arrival (DOA) of an incoming signal relative to a fixed set of coordinates at the DF site. This DF system would in practice be one of several such systems in a coordinated network comprising an emitter locating system. Although absolute accuracy of DOA information is paramount the ability to determine this information in real, or near real, time is generally critical.

Therefore in real applications the ability to determine the angle-of-arrival (AOA) of a signal in a timely manner is the function of a DF system which is utilized in a coordinated search for emitter locations.

A. CONVENTIONAL DIRECTION FINDING TECHNIQUES

There are four basic techniques for generating the data required to determine the AOA, they are:

1) Relative amplitude.
2) Relative phase.
3) Time-of-arrival (TOA).
4) Doppler.

1. Relative Amplitude Techniques

These techniques utilize directional antennas and are quite common below 200-300 MHz. They can be categorized into three general methods.

a. Rotatable Antenna Systems

In this system the entire antenna and therefore the associated directional pattern is rotated about a local axis. The line of bearing to the emitter is determined by observing the angular position of the antenna when the response is either at a maximum or at a minimum value.

b. Rotatable Pattern-Fixed Antenna Systems

Systems in which the antenna is too large to be physically rotated at the desired rate operate by rotating the associated directional pattern of the antenna or array. This rotation is usually accomplished electromechanically. The line of bearing is determined as in the rotatable antenna system.

c. Instantaneous Systems

This system employs two or more antennas and receivers in a direct amplitude comparison of the signal from the overlapping directional patterns of the antennas. The line of bearing is determined by comparison of the relative signal strength in each directional pattern.

2. Relative Phase Techniques

These systems utilize non-directional antennas to obtain directional AOA data. This technique relies on the fact that a wavefront incident upon an antenna system will

be received at the individual antennas in the system with differing phase components. The comparison of the phases will be a direct indication of the AOA of the incoming wavefront (signal).

3. Time of Arrival

This technique requires the time measurement of a given modulation event at two or more antenna locations. The time difference(s) of the event at the antennas is/are then utilized to determine the AOA. This technique is similar to the relative phase technique except that the parameter measured is time vice phase. The requirement for a well defined modulation event is of importance in this method.

4. Doppler

The doppler technique relies on the principle that a receiving system in motion relative to the incident wavefront of a signal will produce an output in the receiving system which is a modulated representation of the original signal. The extraction of this frequency modulation (doppler shift) information is then processed to determine the AOA data [1].

B. DISADVANTAGES OF CONVENTIONAL DF SYSTEMS

All of the above techniques have certain disadvantages. The relative amplitude method produces accuracy in direct relation to the directional ability of the antenna(s). That is a large many wavelength antenna system will produce a narrow beam or beams and therefore the resolving ability

of the system will increase resulting in an overall increase in bearing accuracy. The major drawback to this technique lies in the ability to produce the required antenna within the physical limitations governed by the application. Additionally if the system must be physically rotated then there is an additional design burden imposed on the ability to obtain the required AOA accuracy.

Relative phase techniques lead to ambiguous data unless the separation between the two antenna is small; less than half a wavelength. Although this spacing eliminates ambiguous data due to separation it is in opposition to the requirement for accuracy; accuracy requires wide antenna separation.

Time of arrival methods, while quite good above 1000 MHz especially for pulse signals, rapidly deteriorates below approximately 300 MHz due to difficulties in locating the same modulation event precisely at each antenna location.

Doppler techniques require a circular array of antenna elements with a specified diameter of several wavelengths. The physical size of this antenna system often precludes its use in many applications.

C. A NEW DIRECTION FINDING TECHNIQUE

An approach to providing the required direction finding data utilizing a phase coding scheme similar to that of intrapulse modulation is proposed.

This phase coding technique is similar in philosophy to that attributed to P. M. Woodward for active radar applications [2] and described by G. J. Sieren in his Master's thesis [3].

Basically this technique consists of coding the outputs of several antennas, summing the outputs and then simultaneously producing an pseudo autocorrelation and a cross-correlation output. The antenna outputs are coded utilizing a complementary sequence. The pseudo autocorrelation hereafter called autocorrelation, is accomplished in the usual manner and the cross-correlation is accomplished utilizing a totally orthogonal complementary sequence generated from the original complementary sequence. The output of the matched cross-correlator will be zero and will be unique for a specified angle-of-arrival of the signal. Additionally the output of the matched autocorrelator will be replica of the incoming signal but of an amplitude equal to twice the code length. The angular resolution will only be limited by the ability to physically produce differing sets of delays in the correlators.

The next chapter will discuss phase coding in general providing a brief description of some codes and then a description of complementary sequences (codes) including totally orthogonal complementary sequences (codes) will be given.

With this background the next chapter will describe the proposed direction finding system in detail including results obtained from a digital computer simulation.

The last chapter contains a summary, conclusions and suggestions for further investigation.

The appendix describes the digital computer model including definition of terms, uses and the complete computer source program. The computer program was written in FORTRAN IV, Level G and was processed on an IBM 360/67.

II. PHASE CODING

Phase coding techniques and various phase codes will now be described in order to provide a basis for the following chapter which describes the direction finding technique utilizing phase coding.

A signal can be coded (divided) into n equal segments of duration T. If the only allowable phase states in each segment relative to a reference are zero degrees and one hundred eighty degrees then the coding is termed binary phase coding. If m possible phases are allowed in any one segment then the coding is called polyphase coding. Phase codes can be further subdivided into two general classes depending on the length and the periodicity of the code. The codes can be continuous or confined to a finite time segment. Continuous codes find wide use in communication systems and in CW radars. Coding confined to a finite time segment are generally employed in pulse radar applications. If the code is repetitive it is termed periodic and if not it is termed aperiodic coding. A continuous transmission which has been random binary coded is a special case of aperiodic coding. Coded segments, coded pulses and coded words are in general synonymous terms.

A. POLYPHASE CODES

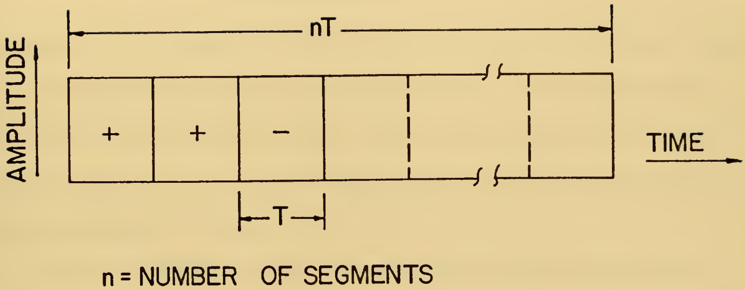
A random binary coding can be described as dividing the carrier into equal segments and assigning a plus (+) or

a minus (-) value to each segment in a random sequence. The plus and minus values refer to no phase reversal (+) and to 180 degrees phase reversal (-) . This representation is shown in figure 2-1a. The amplitude of the kth element in figure 2-1a is a_k. The autocorrelation function of this waveform can be expressed [4] in discrete form as:

$$\Phi(m) = \sum_{k=1}^{n} a_k a_{k+m} \qquad -(n-1) \leq m \leq (n-1)$$

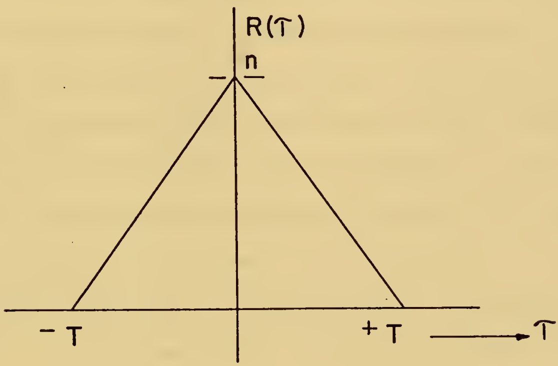
The symbol m is an integer index which steps over the domain shown. Each step corresponds to a shift in a_{k+m} of one segment of duration T. Although this description of the autocorrelation function is not quite accurate this discrete procedure simplifies the calculation and sketching of the autocorrelation function. The autocorrelation function is always maximum at τ (tau) equal zero and is equal to n. For the condition of randomly chosen polarities of a_k and for n large then the autocorrelation function near the origin is triangular as shown in figure 2-1b. The power spectrum of a random sequence, according to the Weiner-Khintchine theorem, is the Fourier transform of its autocorrelation function [5] and therefore the shape of the power spectrum is approximately that for a single segment of length T.

The value of the autocorrelation function away from the origin on the time axis can be shown by utilizing the discrete representation of the autocorrelation function



RANDOM BINARY CODED SIGNAL

FIGURE 2-1a



AUTOCORRELATION OF A RANDOM BINARY CODED SIGNAL

FIGURE 2-1b

described above. Assuming a code as follows, + + + - - + -, and an offset m equal to one segment, then we have:

$$\begin{array}{ccccccccc} + & + & + & - & - & + & - & & \\ & + & + & + & - & - & + & - & \\ \hline & 1 & 1 & -1 & 1 & -1 & -1 & & \end{array}$$

Therefore the value of the autocorrelation function equals zero which is the sum of the products. In forming the products it is assumed that like signs produce a +1 and unlike signs a -1. If m=2 then the application of the above produces a value of $\Phi(m=2) = -1$.

These sidelobes, the value of the autocorrelation function away from the origin are sometimes known as range sidelobes. The reduction of the height of these range sidelobes is of paramount importance in radar applications. The coding of the pulse in a radar system results in an increase in the range resolution due to the pseudo short (width=T) pulse while still retaining the high average power advantage of the long pulse (width=nT). For a long random code the value of the range sidelobes will vary between $\pm$ 0.77n with a probability of 0.5 [4].

Polyphase codes can be generated for the periodic case which will have zero periodic correlation except for a shift equal to zero [6].

The correlation function will have the familiar triangular shape for a rectangular pulse input. A modulation code of length n can be expressed as a sequence $\{a_o, a_1, a_2, \ldots, a_{n-1}\}$. The periodic correlation function is defined to be the sequence $\{x_o, x_1, x_2, \ldots, x_{n-1}\}$. The

general function x_i is as shown below.

$$x_i = \sum_{k=0}^{n-1} a_{k+1} a_k^* \qquad \text{Where: * denotes the complex conjugate.}$$

The definition of the autocorrelation function will result in values for integer shifts. The sequence $\{a_o, a_1, \ldots, a_{n-1}\}$ can be generated for any given code length $n=p^2$. Where p is a prime number greater than unity. The operations are as follows.

1. For a given code length n pick the prime number p.
2. Find all the pth roots of unity. That is roots of the form $e^{-j(2\pi k/p)}$ for $0 \leq k \leq p-1$.
3. Form the sequences of length p as follows:

$$\begin{array}{lllll}
1, & 1, & 1, & \ldots & 1 \\
1, & R_1, & R_1^2, & \ldots & R_1^{p-1} \\
\cdot & \cdot & \cdot & & \cdot \\
\cdot & \cdot & \cdot & & \cdot \\
\cdot & \cdot & \cdot & & \cdot \\
1, & R_{p-1}, & R_{p-1}^2, & \ldots & R_{p-1}^{p-1}
\end{array}$$

   The p roots of unity are: $1, R_1, R_2, \ldots, R_{p-1}$.
4. The code sequence is formed by writing in serial order column one, column two, column three, etc.

This code thus formed has a correlation function x_i which has a zero value everywhere except for $i=0$, p^2, $2p^2$, $3p^2$, etc. Although this is a good code (all zeros except main peaks) it suffers from the requirement that there be p different phase shifts in the code.

The restriction that p be a prime number has been proven [7] by R. I. Frank and S. A. Zadoff and confirmed by R. C. Heimiller not to be a prerequisite. Heimiller had originally specified p to be prime.

A patent by S. A. Zadoff and W. Abourezk [8] utilized a basic form of the Frank code sequence to describe a matrix as follows:

$$\begin{vmatrix} 1, & 2, & 3, & 4, & \cdots & p \\ 2, & 4, & 6, & 8, & \cdots & 2p \\ 3, & 6, & 9, & 12, & \cdots & 3p \\ 4, & 8, & 12, & 16, & \cdots & 4p \\ \vdots & \vdots & \vdots & \vdots & & \vdots \\ p & & \cdots & & \cdots & p^2 \end{vmatrix}$$

There are p rows and p columns. The numerals represent the multiplying coefficients of a basic phase angle. The basic phase angle is defined as $2\pi r/p$ where r is relatively prime to p and r and p are integers. Letting R equal the primitive pth root of unity then the following matrix is formed.

$$\begin{vmatrix} R & R^2 & R^3 & \cdots & R^p \\ R^2 & R^4 & R^6 & \cdots & R^{2p} \\ R^3 & R^6 & R^9 & \cdots & R^{3p} \\ \vdots & \vdots & \vdots & & \vdots \\ R^p & & & \cdots & R^{p^2} \end{vmatrix}$$

Where the exponents of R are given by the first matrix. This is just a permutation of Heimiller's derivation. Heimiller's proof [6] of the good properties of the auto-correlation function applies equally as well to the above for p not prime. A special case is p=2 the binary case. For p=2 the 2x2 matrix of the pxp matrix is used as follows:

2x2 matrix $$\begin{vmatrix} 1 & 2 \\ 2 & 4 \end{vmatrix}$$

then $$\begin{vmatrix} R & R^2 \\ R^2 & R^4 \end{vmatrix}$$ where $R = e^{-j(2\pi r/p)}$

$= e^{-j(2\pi r/2)}$

$= e^{-j(\pi r)}$

and $$\begin{vmatrix} e^{-j\pi} & e^{-j2\pi} \\ e^{-j2\pi} & e^{-j4\pi} \end{vmatrix} = \begin{vmatrix} -1 & 1 \\ 1 & 1 \end{vmatrix}$$

Therefore the code sequence is: -1, 1, 1, 1.

Polyphase codes with good non-periodic properties can be generated by a permutation of the previously given matrix [9]. This matrix is:

$$\begin{vmatrix} 0 & 0 & 0 & 0 & \cdots & 0 \\ 0 & 1 & 2 & 3 & \cdots & (p-1) \\ 0 & 2 & 4 & 6 & \cdots & 2(p-1) \\ 0 & 3 & 6 & 9 & & 3(p-1) \\ \vdots & \vdots & \vdots & \vdots & & \vdots \\ 0 & \cdots & & & \cdots & (p-1)^2 \end{vmatrix}$$

The phase angle is still $2\pi r/p$ with r relatively prime to p. For clarity the periodic philosophy will be restated.

1. The code sequence is formed by writing the matrix a column at a time.
2. The entire code is periodic that is the matrix is repeated.
3. The autocorrelation function is everywhere zero except at multiples of the code period where it is a single maximum.

A non-periodic code can be formed by selecting a starting point, running through the matrix once and stopping. The assumption in doing this is that there is zero amplitude before and after the sequence. There will be more than p^2 starting points. The position in the matrix where the phase changes are the least drastic will be the starting point. This position seen by inspection is the upper left hand corner of the above matrix.

For a code of length n=16 the basic phase angle is euqal to $2\pi r/p$ where r=1 is the primitive pth root and therefore the general element in the matrix is $e^{-j(2\pi/p)}$. The non-periodic exponent matrix is:

$$\begin{vmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 2 & 3 \\ 0 & 2 & 4 & 6 \\ 0 & 3 & 6 & 9 \end{vmatrix}$$

and the non-periodic phase matrix is:

$$\begin{vmatrix} 1 & 1 & 1 & 1 \\ 1 & e^{-j\pi/2} & -1 & e^{+j\pi/2} \\ 1 & -1 & 1 & -1 \\ 1 & e^{+j\pi/2} & -1 & e^{-j\pi/2} \end{vmatrix}$$

The code sequence is obtained by writing in serial form column one, column two, column three and column four as follows:

$1, 1, 1, 1, e^{-j\pi/2}, -1, e^{+j\pi/2}, 1, -1, 1, -1, 1, e^{+j\pi/2}, -1, e^{-j\pi/2}$

This code has four phase states: zero, 90, 180 and 270 degrees. The autocorrelation function for n=16 shows [9] that the main peak is equal to 16 and the maximum sidelobe is 1.4. This value for the maximum sidelobe is found by the vector addition of p/2 unit vectors at a phase angle of $2\pi/p$ for p=even or the vector sum of $(p+1)/2$ unit vectors at the phase angle $2\pi/p$ for p=odd.

There is a class of binary coded pulses whose autocorrelation over one period (finite time autocorrelation) has only two non-zero sidelobe levels. These codes are called perfect words and include Barker codes. The known Barker codes are the following.

Code Length	Code
2	+ -
3	+ + -
4	+ + + - and + + - +

Code Length	Code
5	+ + + − +
7	+ + + − − + −
11	+ + + − − − + − − + −
13	+ + + + + − − + + − + − +

The autocorrelation function for these codes is:

$$\Phi(m) = \begin{cases} n & \text{if } m = 0 \\ \text{zero or } \pm 1 & \text{if } m \neq 0 \end{cases}$$

B. COMPLEMENTARY SEQUENCES

All these polyphase codes including the binary phase codes have the property that the autocorrelation function is maximum at τ (tau) equal to zero but all including the perfect words have autocorrelation sidelobes which have non-zero values.

There is a series of binary elements known as complementary series which eliminates this non-zero sidelobe problem.

A complementary series is defined by M. J. E. Golay [10] to be a pair of equally long finite sequences of two kinds of elements which have the property that the number of pairs of like elements with any one given separation in one series is equal to the number of pairs of unlike elements in the other series with the same separation. If the two kinds of elements in the series are +1 and -1 then the sum of their autocorrelation functions is everywhere zero except for the center term.

Assume a complementary sequence pair of length equal to four as follows with the two elements being +1 and -1.

Code A .... +1, +1, +1, -1

Code B .... +1, +1, -1, +1

Code A has exactly two pairs of adjacent like elements (+1, +1, ... +1, +1) while code B has exactly two pairs of adjacent unlike elements (+1, -1, ... -1, +1). Additionally for elements spaced by one intervening element code A has exactly one pair of like elements (+1, +1) and code B has exactly one pair of unlike elements (+1, -1). These like and unlike combinations continue for all N-1 possible separations where N equals the number of elements in the series.

Golay has shown [10] that N must always be an even number and must be the sum of two squares. Therefore the possible values for a code length up to for example 50 are 2, 4, 8, 10, 16, 18, 20, 26, 34, 36, 40, and 50.

Kernals are basic code lengths which cannot be decomposed into shorter lengths. Kernals exist for codes of length 2, 10 and 26 [10,11]. Golay has shown [10] that there are 2^6 pairs of complementary series (some identical) which can be generated by the following six operations on a given pair of a complementary series.

1. Interchanging the series.
2. Reversing the first series.
3. Reversing the second series.
4. Altering the first series.
5. Altering the second series.
6. Altering the elements of the even order of each series.

Altering a series embodies interchanging the kinds of elements. For example the element +1 becomes -1 and conversely the element -1 becomes +1.

As an example of the above operation consider the following example. The original code is: +1, +1, +1, -1 and +1, +1, -1, +1 and the operations are the following.

1. Interchange .... +1, +1, -1, +1 and +1, +1, +1, -1
2. Reverse-first ..... -1, +1, +1, +1 and +1, +1, -1, +1
3. Reverse-second .... +1, +1, +1, -1 and +1, -1, +1, +1
4. Alter=first .... -1, -1, -1, +1 and +1, +1, -1, +1
5. Alter-second ...... +1, +1, +1, -1 and -1, -1, +1, -1
6. Alter-even order .. +1, -1, +1, +1 and +1, -1, -1, -1

All of the above codes and the remainder of the sixty-four combinations will maintain the properties of complementary series.

Golay has shown [10] and Jauregui has proved [11] that longer codes can be generated from the kernal by certain transformations. Given a complementary sequence pair A and B with elements $a_1, a_2, \ldots a_{n-1}$,an and $b_1, b_2, \ldots b_{n-1}, b_n$ respectively then a longer complementary sequence pair can be written as C = AB and D = A$\overline{B}$, where AB is $a_1, a_2 \ldots a_n, b_1, b_2, \ldots b_n$ and A$\overline{B}$ is $a_1, a_2 \ldots a_n, \overline{b}_1, \overline{b}_2 \ldots \overline{b}_n$. Another operation which will produce valid longer complementary sequences is the interlacing of the elements. A sequence can be written C = A <u>interlace</u> B and D = A <u>interlace</u> $\overline{B}$. <u>Interlace</u> is defined to be $a_1, b_1, a_2, b_2, \ldots a_n, b_n$ as required for C and D. Once the longer codes have been written by either

method then even longer codes can be constructed utilizing the newly created sequence as the given sequence for A and B. This operation can be carried on to any desired code length. The longer code length will be a function of the original code length N.

It is therefore evident that 2^6 (64) valid combinations of a kernal can be generated and from any of these complementary codes of longer length can be constructed.

Totally orthogonal complementary sequences can be generated such that the two pairs of complementary sequences when cross-correlated produce only zeros. C. E. French [12] in his Master's thesis has shown that every complementary code set has exactly one set of two codes that are totally orthogonal to it. It is only necessary to know the kernals for the original complementary code in order to construct the totally orthogonal code. The operation on the complementary sequence pair to form the totally orthogonal sequence is given by French [12] as follows. Given a complementary sequence pair A and B then the totally orthogonal sequence pair is $\underline{\bar{B}}$ and $\underline{A}$. The overbar defines the altering of the elements as previously described and the underbar defines the inversion of the order of the elements. The cross-correlation of A with $\underline{\bar{B}}$ added to the cross-correlation of B with $\underline{A}$ will result in the null vector (all zeros). An example of a totally orthogonal sequence pair is shown below.

Original code .... +1, +1, +1, -1 and +1, +1, -1, +1

Orthogonal code .. -1, +1, -1, -1 and -1, +1, +1, +1

B. P. Schweitzer [13] describes generalized complementary code sets including non-interacting (totally orthogonal) sets in his Doctoral dissertation and extends the code sets to include other than binary elements.

A. G. Fabula, J. H. Whitehouse, J. M. Speiser and others [14,15] have done some preliminary work in an attempt to beam form single codes at the Naval Undersea Warfare Center, San Diego, California.

Ultrasonic delay lines have been investigated [16,17, 18] by J. V. Vollmer, J. H. Whitehouse and J. M. Speiser as devices which can be used to physically realize the coding of a signal.

III. THEORY AND MODELING

Coding theory has been widely used for the coherent transmission and reception of electromagnetic signals to enhance certain aspects of communication and radar systems. The system generally involves the controlled transmission of information. By controlled it is meant that the system has control over the transmission as well as the reception of the signal. This coherent feature is responsible for the success of these coded systems.

Direction finding is involved only with the reception of the signal. The sorting out of the angle-of-arrival information has historically been accomplished by uniquely defining the amplitude, phase or time for a given AOA. These methods were briefly discussed in chapter one.

A. THEORY OF OPERATION

The technique presented here involves a combination of parameters. The combining, amplifying and altering of the individual received signals at each antenna result in a unique signal which upon processing provides the desired AOA information.

The type of antenna required is not critical, any omnidirectional antenna can be used. The only important criterion is that the antennas must be quite similar, if not nearly indentical in receiving characteristics. The antenna separation should be such that mutual coupling

between antennas is held to a minimum. The antennas do not form into an array but rather into a corporate set. The number of antennas required will be a function of the code length. The individual antennas can be any design (voltage probes for example) as long as the resultant antenna patterns are omnidirectional. A sketch of an antenna group for four antennas is shown in figure 3-1. The separation between the antennas need not be uniform but rather can be any value provided the spacing is known. In practice the separation should be as uniform as possible to reduce the complexity of the correlation receiver.

The next functional group after the antennas is the signal encoder. The function of this group is to phase code each individual antenna output and then to combine the individually encoded signals so that this summed signal can be applied to a signle transmission line. A typical signal encoder for a code of length equal to four is depicted in figure 3-2. The signal from each antenna is applied to a two output multicoupler type device which can provide both a normal (plus in-plus out) output and an inverted (plus in-negative out) output. All the normal and inverted outputs will be identical except for the delay due to antenna separation and the built in 180 degree shift separating the normal and the inverted outputs. For a signal incident upon the antenna system as shown in figure 3-1 for an AOA equal to zero degrees (θ=zero) the phase delay due to antenna separation is equal to the antenna

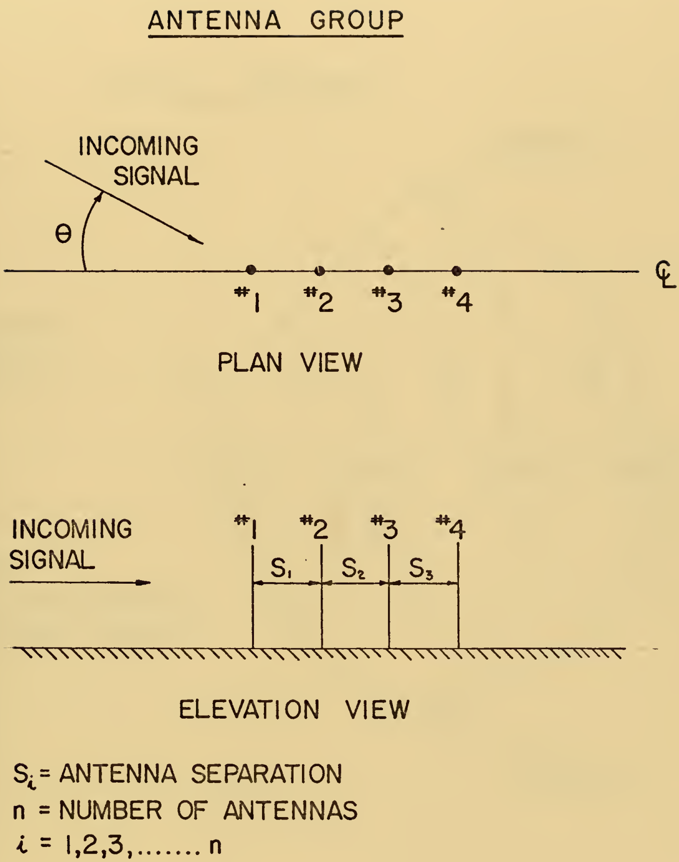

ANTENNA GROUP
INCOMING SIGNAL
θ
#1
#2
#3
#4
℄
PLAN VIEW
INCOMING SIGNAL
#1
#2
#3
#4
S1
S2
S3
ELEVATION VIEW
Si = ANTENNA SEPARATION
n = NUMBER OF ANTENNAS
i = 1,2,3,....... n

FIGURE 3-1

SIGNAL ENCODER

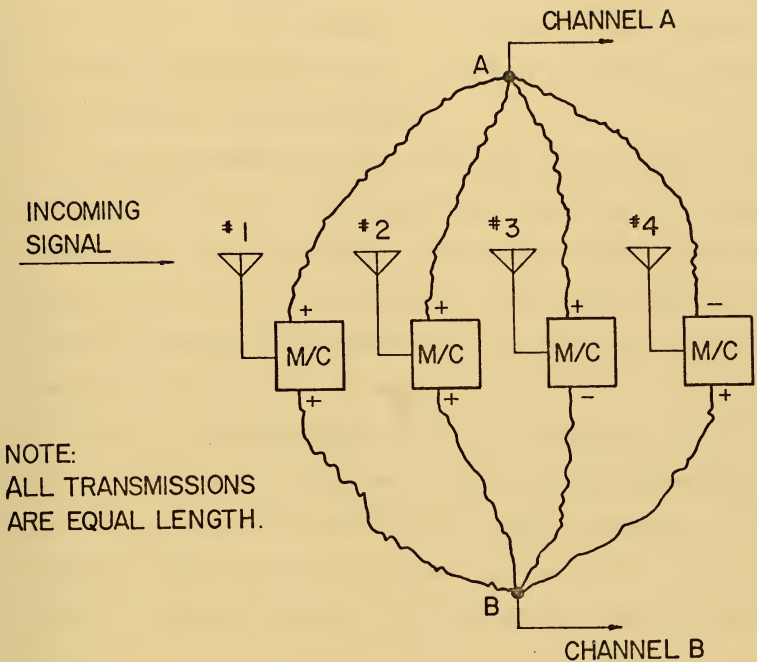


FIGURE 3-2

separation. The phase delay due to antenna separation will reduce to zero as the AOA of the signal moves off and becomes normal to the line of the antennas. The phase delay varies from maximum to zero in accordance with the cosine of the AOA of the signal. A signal which propagates along the line of antennas has an AOA of zero degrees and a signal propagating normal to the line of the antennas has an AOA of ninety degrees.

For the example of four antennas there would be eight outputs available. The appropriate normal and inverted outputs are then combined as required for the complementary code in use. For example if the code length is four then the required complementary code would be the two sequences +1, +1, +1, -1 and +1, +1, -1, +1. The +1 indicates a normal output and the -1 indicates an inverted output. If the antenna nearest the arriving wavefront is #1 and the next #2 and so forth, then the signals at the antenna side of point A (figure 3-2) would be normal, normal, normal, inverted. At the antenna side of point B (figure 3-2) the signals would be normal, normal, inverted, normal. Since the individual antennas are separated in space then the phase separations referenced to antenna #1 is: antenna #2 one delay, antenna #3 two delays, antenna #4 three delays.

If an incoming signal as shown in figure 3-3 with an AOA of zero degrees is assumed then the signals at the antenna outputs would be as shown in figure 3-4 and the

INCOMING SIGNAL

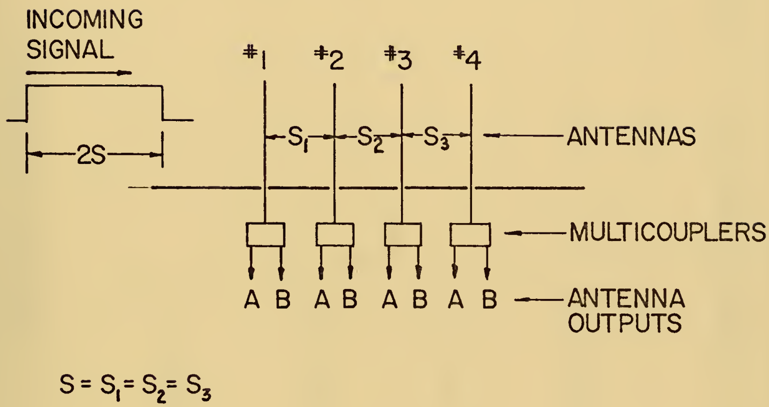
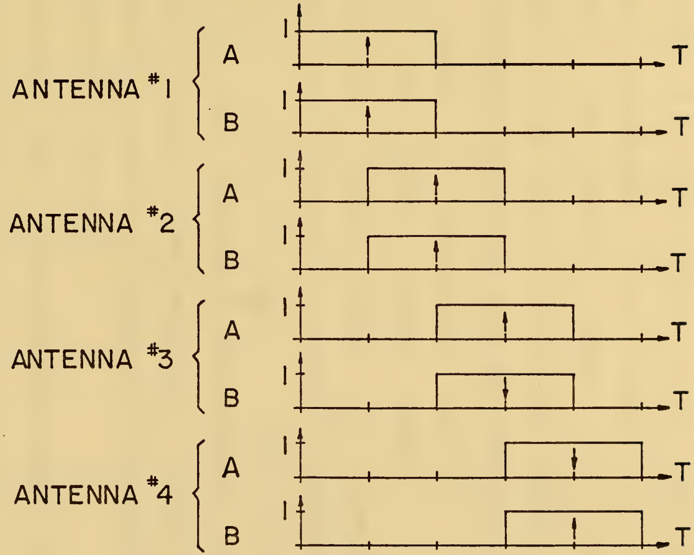


FIGURE 3-3

ANTENNA OUTPUTS



NOTE: THE UP ARROW (↑) INDICATES A NORMAL OUTPUT,
THE DOWN ARROW (↓) INDICATES AN INVERTED OUTPUT.

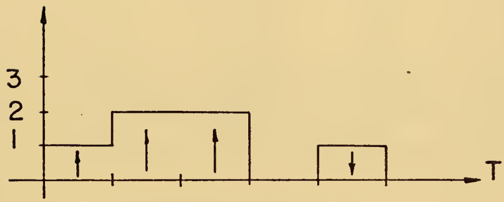
FIGURE 3-4

summed signals at points A and B would be as shown in figure 3-5. The coded and summed signals at points A and B are now available for transmission from the antenna location to a central processing point. A distinct advantage inherent in this technique is the reduction in the number of transmission lines required from the antenna location to the processing location. Each of the two channels A and B contain all the data required to not only determine the AOA but also the information contained in the signal. The simultaneous extraction of the DF data and the signal itself is somewhat unique.

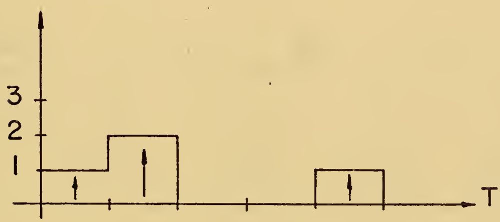
The coded and summed signals that is channel A and channel B are each applied to banks of tapped delay lines in the correlation type receiver. Figure 3-6 depicts a typical unit of this section of the system. The terms autocorrelation and cross-correlation are used to describe the operation depicted in figure 3-6 and delineated in the following paragraph.

The delay lines for the autocorrelation and the cross-correlation outputs are identical and there is one set of delay lines for each AOA for each channel. The outputs in each delay line tap are both a portion of the autocorrelation output and the cross-correlation output. The autocorrelation output is the time inversion of the antenna code. For example if the antenna code for a four antenna system is +1, +1, +1, -1 and +1, +1, -1, +1 then the autocorrelation output is -1, +1, +1, +1 and +1, -1, +1, +1.

CODED & SUMMED SIGNALS



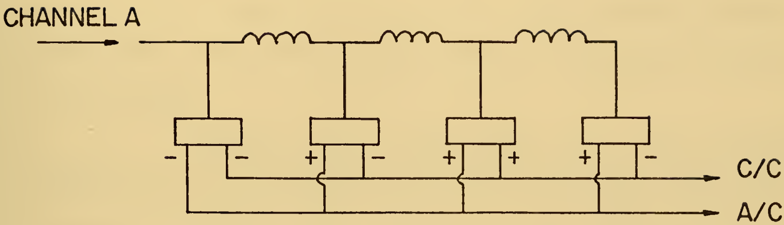
CHANNEL A — POINT A



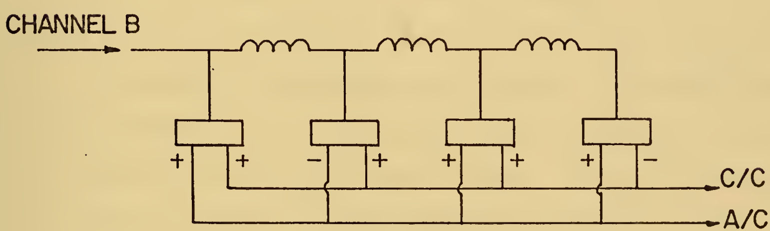
CHANNEL B — POINT B

FIGURE 3-5

CORRELATORS



CORRELATOR — A



CORRELATOR — B

C/C : CROSS-CORRELATION OUTPUT.

A/C : AUTOCORRELATION OUTPUT.

FIGURE 3-6

The cross-correlation output is the complement of the second sequence in the antenna code and a duplication of the first sequence in the antenna code. For example for the antenna code above the cross-correlation output is -1, -1, +1, -1 and +1, +1, +1, -1. The following table summarizes the antenna coding and the associated correlation output.

	Antenna code	Autocorrelation	Cross-correlation
Channel A	+1, +1, +1, -1	-1, +1, +1, +1	-1, -1, +1, -1
Channel B	+1, +1, -1, +1	+1, -1, +1, +1	+1, +1, +1, -1

The outputs from the autocorrelator and the cross-correlator are each summed. The resultant outputs from each correlator are shown in figure 3-7 for an exact match. An exact match occurs where the delays in the correlators are identical to the delays at the individual antennas. The autocorrelation outputs, A and B are summed directly point by point to produce the required signal output. This final output as shown in figure 3-8 and termed the autocorrelator output exhibits a zero sidelobe level and a mian lobe consisting of a duplication of the original input signal with an amplitude equal to eight times the original value. The multiplying factor of eight is due to the utilization of a code of length four since the summed output has a value equal to twice the code length. The two cross-correlation outputs are also summed directly point by point and for this matched condition produce a zero value

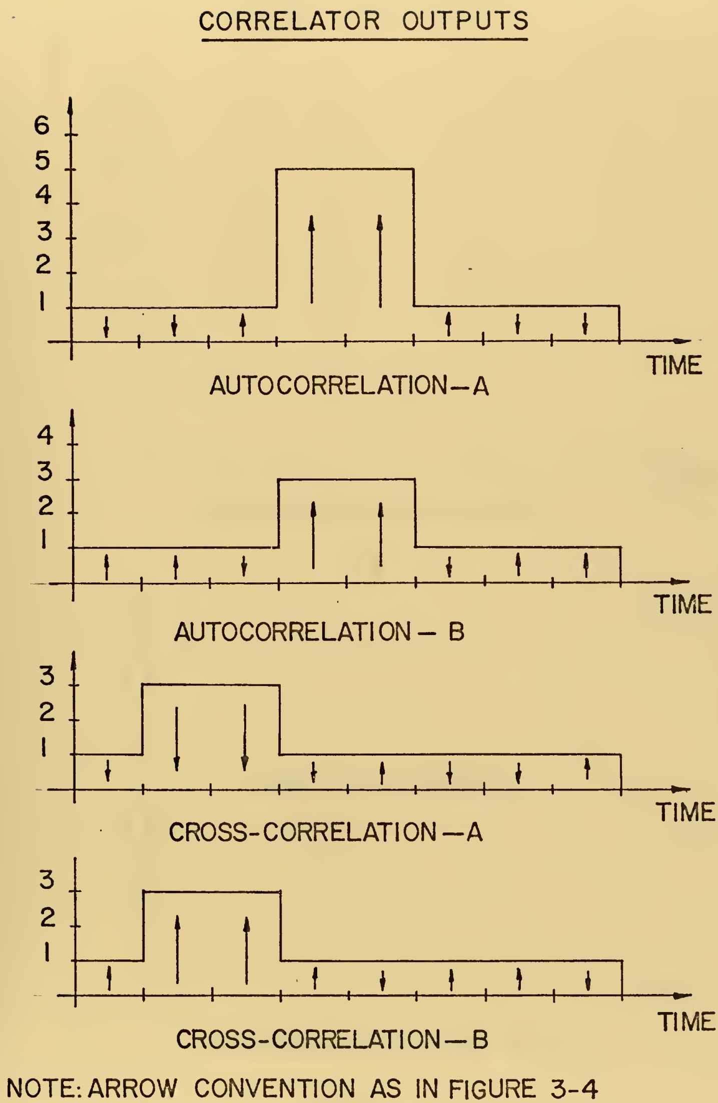
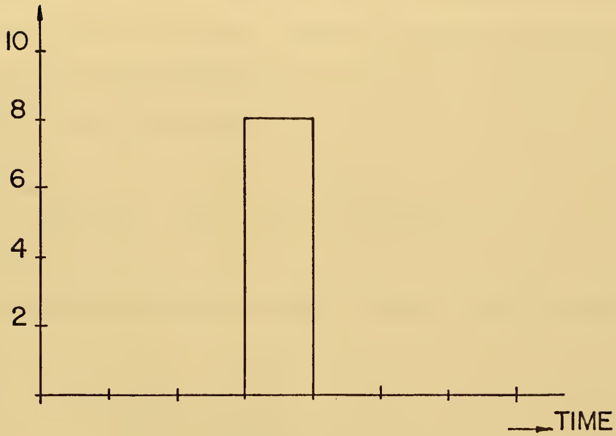
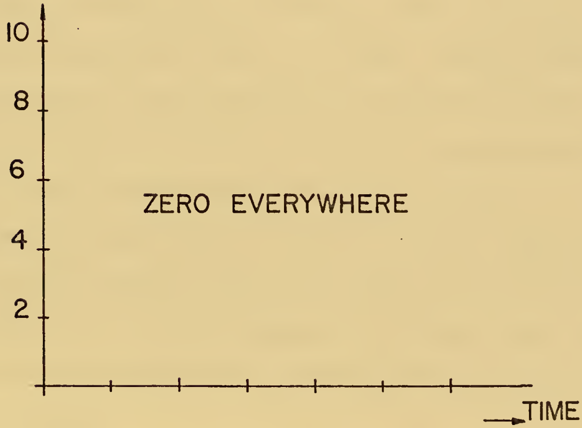

CORRELATOR OUTPUTS
6
5
4
3
2
1
TIME
AUTOCORRELATION—A
4
3
2
1
TIME
AUTOCORRELATION— B
3
2
1
TIME
CROSS-CORRELATION—A
3
2
1
TIME
CROSS-CORRELATION—B
NOTE: ARROW CONVENTION AS IN FIGURE 3-4

FIGURE 3-7

FINAL OUTPUTS



AUTOCORRELATOR OUTPUT



CROSS-CORRELATOR OUTPUT

FIGURE 3-8

for all time. This summed signal is shown in figure 3-8 and is termed the cross-correlator output.

In summary if the antenna code is composed of elements a_i and b_i $(i=1,2,\ldots n)$ for a code of length n and for j = number of possible separations $(j=0,1,2,\ldots n-1)$ then the autocorrelation series are:

$$c_j = \sum_{i=1}^{i=n-j} a_i a_{i+j} \quad \text{and} \quad d_j = \sum_{i=1}^{i=n-j} b_i b_{i+j}$$

The final autocorrelation output (figure 3-8) is given by:

$$c_j + d_j = \begin{cases} 0 & j \neq 0 \\ 2n & j = 0 \end{cases}$$

In like manner for a cross-correlation code with the above antenna code and j as defined above the final cross-correlation output is $e_j + f_j$ = zero for all values of j where e_j and f_j are the cross-correlation series. The cross-correlation series e_j and f_j are constructed similarly to the autocorrelation series c_j and d_j.

It can be seen from the preceding that every delay in the ninety degrees from an AOA equal to zero degrees to an AOA equal to ninety degrees is unique since the cosine of the AOA takes on a unique value for all angles in this quadrant.

Signals arriving in the other quadrants 090 to 180, 180 to 270 and 270 to 000 are processed in a similar manner. The antenna code and the correlator outputs are identical in the 000 to 090 and the 270 to 000 quadrants therefore

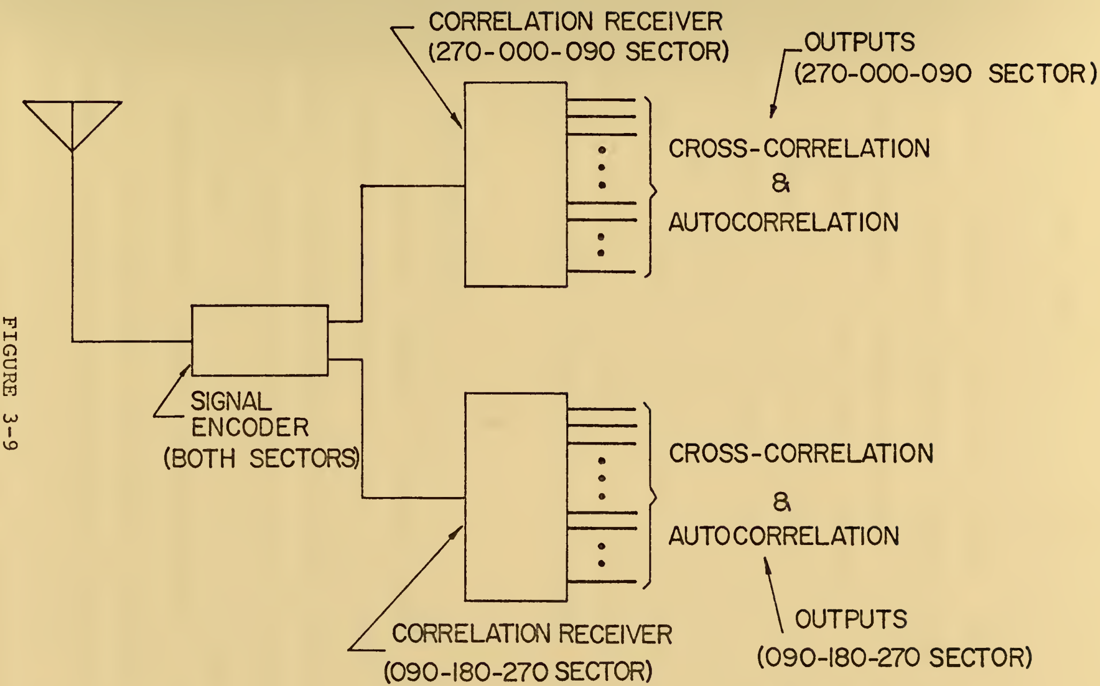
the only addition to the system for this region is the incorporation of a simple auxiliary antenna group. This antenna and associated detectors is used to sort out the two quadrants by relative signal strength. The ambiguity in this sector is resolved in favor of the stronger signal appearing in the auxiliary antenna. The auxiliary antenna is required to have two unidirectional patterns physically displaced by 180 degrees. Two individual antennas with essentially cardioid patterns are adequate for this function. The antenna code and the correlator outputs are identical for the 090 to 180 and the 180 to 270 quadrants. The antenna code utilized in this region is the time inverse of the code utilized for the 270-000-090 region since the signals arrive at the antenna from the "rear" relative to the signals in the 270-000-090 region. An additional auxiliary antenna group and detectors are required to sort out the two quadrants in this "rear" region.

An ambiguity exists for elevation angles greater than zero degrees. The preceding discussion was limited to zero elevation angle signals. For non zero elevation angle signals the actual delay is the zero elevation angle delay multiplied by the cosine of the elevation angle. The indicated angle resulting after processing will be in error. The error will be such that the value of the cosine of the true zero elevation angle AOA would be reduced by the cosine of the elevation angle. The resulting

angle as processed by the receiver will be increased in value from the true AOA for the 000-090 and 180-270 quadrants and reduced in value for the 090-180 and 270-000 quadrants. The error is small for low elevation angles and also small for angles-of-arrival greater than 10-15 degrees off the line of the array.

In operation the outputs of the cross-correlators are scanned to find the unique output with the zero value. All unmatched cross-correlators will have an output and the matched cross-correlator will have no (zero) output. The outputs are indexed according to the AOA represented by the delay lines therefore the AOA is known as soon as the zero cross-correlator output is located. The auto-correlator output for the identical delay line is the signal of interest which has been increased in signal to noise ratio by the correlation gain. Figure 3-9 is a simplified block diagram of the complete system. The frequency selection circuits of the system included in the correlator receiver are the usual devices utilized to pass a selected frequency and reject all others. The output of the system is therefore unique in two domains. The frequency selection section sorts through the frequency domain and selects the frequency of interest and the correlation processor sorts through the spatial domain and a determination of the AOA is made.

A computer model was developed and utilized to search for ambiguities and to determine the limiting factor(s)



SIMPLIFIED BLOCK DIAGRAM

FIGURE 3-9

affecting accuracy. The hoped for results of no ambiguities in a given quadrant was verified and the accuracy to which the AOA could be resolved was shown to be primarily a function of the delay lines. That is if delay lines could be physically realized which were unique for each degree of coverage required then the resolution of the system is in one degree increments. If delay lines stepped in delay by 0.5 degree are realizable then the resolution is in 0.5 degree steps and so on for any delay line increment. In practice if an AOA fell between two delay lines due to the discrete nature of the lines then the output to be scanned for would be the minimum. In the exact match case this smallest output is equal to zero.

B. SYSTEM MODELING

The system was modeled utilizing a digital computer to provide for flexibility of inputs and also to provide a means of obtaining permanent annotated data plots. The computer program is discussed in detail in the appendix and therefore it will not be detailed in this section.

Essentially the simulation provides for an input signal of any character, any number of antennas, a signal encoder, a correlation receiver and a graphical output. Any valid complementary code can be utilized. The program will generate the proper number of signals and subject to the users command will produce either an autocorrelation

or a cross-correlation output plotted as amplitude versus time. Additionally bounds can be placed on the time range over which the correlation takes place. The user can also command the program to produce the plotted output over any range of angles and stepped in any increment of angle and any degree of delay line mismatch.

Although any code length can be utilized with this program a code length equal to sixteen was arrived at as a good typical code length. Additionally since the information obtained in one ninety degree quadrant is essentially common with the other three ninety degree quadrants the investigation was limited to the range of incoming signals in the 000-090 degree quadrant. The elevation angle utilized was zero degrees.

1. <u>Autocorrelation Results</u>

The incoming signal utilized was a pulse equal in time duration to twice the maximum antenna separation time delay. The time duration of the correlation process was sufficient to encompass all pre-summed sidelobes generated by the correlation receiver. The amplitude of the incoming signal was taken to be unity. The input signal time computation increments were carefully arrived at in order to have a priori information to aid in the analysis of the data plots.

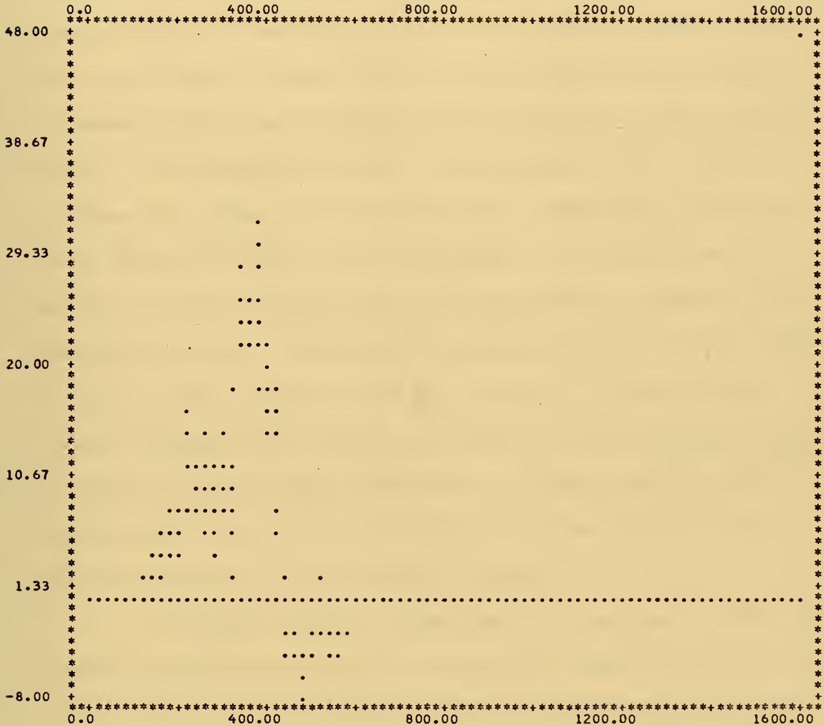
The first plot figure 3-10 shows the result of autocorrelation with a completely mismatched correlator. That is the delay in the correlator is far removed from

THE FOLLOWING DATA IS FOR A NEW ANGLE OF ARRIVAL.

ANGLE OF ARRIVAL= 60.0...THIS FILTER IS MATCHED TO 72.6.

TIME IS PLOTTED ALONG THE X-AXIS AND THE FILTER OUTPUT IS PLOTTED ALONG THE Y-AXIS.......DISREGARD 0.0/0.0 AND 1600.0/48.0THEY ARE USED TO SCALE THE PLOT.

THE FILTER DELAY=0.600 TIMES THE ANTENNA SEPARATION



X-SCALE: "*"= 0.200E 02 UNITS

Y-SCALE: "*"= 0.933E 00 UNITS

THE TIME OF OCCURANCE OF THE CENTER OF THE MAIN LOBE IS 372.50.

THE WIDTH OF THE MAIN LOBE IS 3.00.

THE LEADING EDGE OF THE MAIN LOBE OCCURS AT 371.00.

FIGURE 3-10

the actual matched value. The label above the plot stating that the filter delay equals X.XXX times the antenna separation indicates the degree of mismatch. The delay line filter is matched to the incoming signal when the value of X.XXX is 1.000. The angle to which the filter (correlator) is matched is also indicated on the printout. The next plots figures 3-11 to 3-15 show a much closer agreement with the matching of the filter to the required delay. The expected output for an exact match will be a rectangular pulse of original width (duration) and amplitude equal to twice the code length. In this case the width is 100 time units and the amplitude is equal to 32 amplitude units. Although the output is not "clean" the correct output can be seen in the plot. This correct output becomes more and more evident as the filter delay approaches the matched condition. Figure 3-16 is for the matched case. The predicted 100 time units by 32 amplitude units is the correct output.

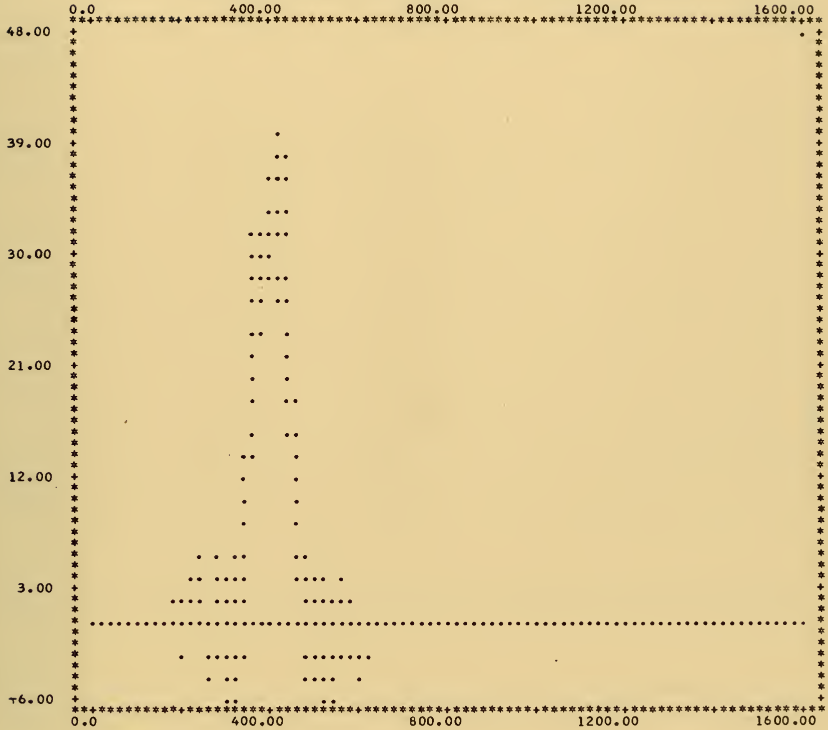
A unique factor concerning this output is that the leading edge of the pulse is delayed a specific delay for a specific angle-of-arrival. As the angle changes value the pulse "walks" towards the left hand ordinate. The delay from the left-hand ordinate is equal to the antenna delay for the angle-of-arrival times N-1 where N equals the number of antennas. Figures 3-17 to 3-21 show this shift in the output. Therefore the AOA can be determined from the delay of the leading edge of the pulse. While

THE FOLLOWING DATA IS FOR A NEW ANGLE OF ARRIVAL.

ANGLE OF ARRIVAL= 60.0...THIS FILTER IS MATCHED TO 63.3.

TIME IS PLOTTED ALONG THE X-AXIS AND THE FILTER OUTPUT IS PLOTTED ALONG THE Y-AXIS.......DISREGARD 0.0/0.0 AND 1600.0/48.0THEY ARE USED TO SCALE THE PLOT.

THE FILTER DELAY=0.900 TIMES THE ANTENNA SEPARATION



X-SCALE: "*"= 0.200E 02 UNITS

Y-SCALE: "*"= 0.900E 00 UNITS

THE TIME OF OCCURANCE OF THE CENTER OF THE MAIN LOBE IS 401.00.

THE WIDTH OF THE MAIN LOBE IS 68.00.

THE LEADING EDGE OF THE MAIN LOBE OCCURS AT 367.00.

FIGURE 3-11

THE FOLLOWING DATA IS FOR A NEW ANGLE OF ARRIVAL.

ANGLE OF ARRIVAL= 60.0...THIS FILTER IS MATCHED TO 62.6.

TIME IS PLOTTED ALONG THE X-AXIS AND THE FILTER OUTPUT IS PLOTTED ALONG THE Y-AXIS.......DISREGARD 0.0/0.0 AND 1600.0/48.0THEY ARE USED TO SCALE THE PLOT.

THE FILTER DELAY=0.920 TIMES THE ANTENNA SEPARATION

X-SCALE: "*"= 0.200E 02 UNITS

Y-SCALE: "*"= 0.933E 00 UNITS

THE TIME OF OCCURANCE OF THE CENTER OF THE MAIN LOBE IS 408.00.

THE WIDTH OF THE MAIN LOBE IS 74.00.

THE LEADING EDGE OF THE MAIN LOBE OCCURS AT 371.00.

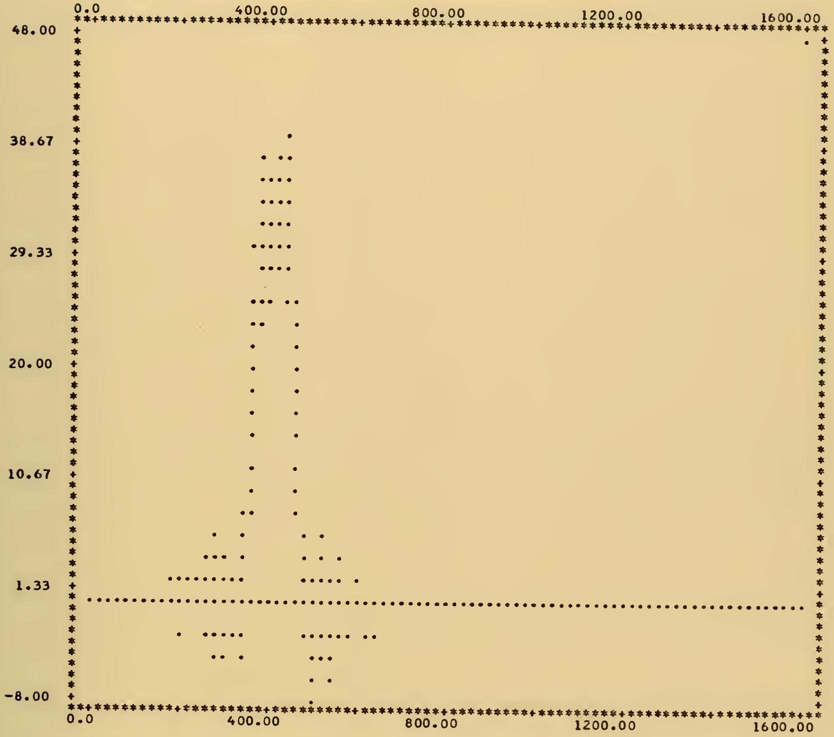
FIGURE 3-12

THE FOLLOWING DATA IS FOR A NEW ANGLE OF ARRIVAL.

ANGLE OF ARRIVAL= 60.0...THIS FILTER IS MATCHED TO 62.0.

TIME IS PLOTTED ALONG THE X-AXIS AND THE FILTER OUTPUT IS PLOTTED ALONG THE Y-AXIS........DISREGARD 0.0/0.0 AND 1600.0/48.0THEY ARE USED TO SCALE THE PLOT.

THE FILTER DELAY=0.940 TIMES THE ANTENNA SEPARATION



X-SCALE: "*"= 0.200E 02 UNITS

Y-SCALE: "*"= 0.933E 00 UNITS

THE TIME OF OCCURANCE OF THE CENTER OF THE MAIN LOBE IS 408.00.

THE WIDTH OF THE MAIN LOBE IS 74.00.

THE LEADING EDGE OF THE MAIN LOBE OCCURS AT 371.00.

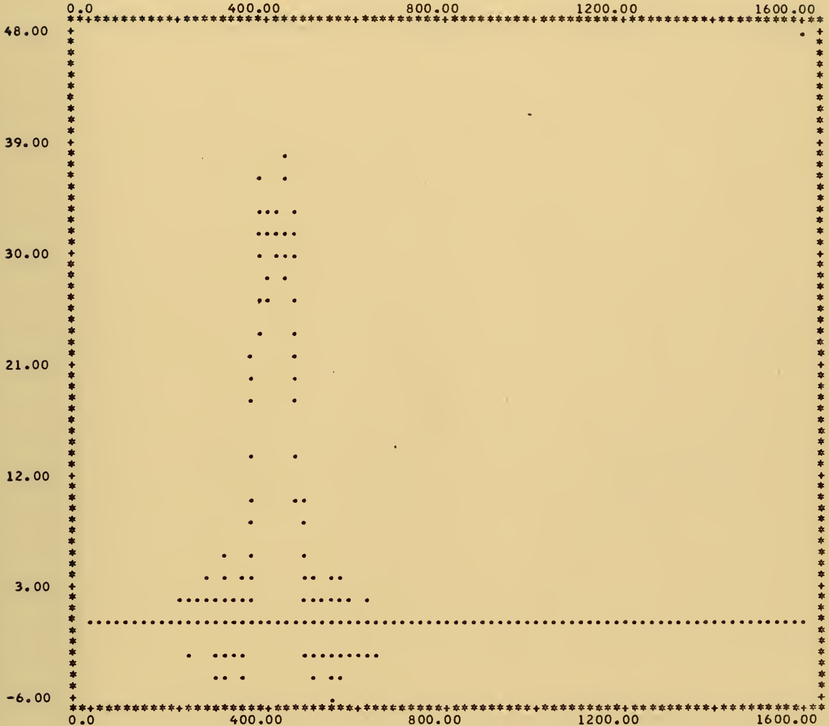
FIGURE 3-13

THE FOLLOWING DATA IS FOR A NEW ANGLE OF ARRIVAL.

ANGLE OF ARRIVAL= 60.0...THIS FILTER IS MATCHED TO 61.3.

TIME IS PLOTTED ALONG THE X-AXIS AND THE FILTER OUTPUT IS PLOTTED ALONG THE Y-AXIS........DISREGARD 0.0/0.0 AND 1600.0/48.0THEY ARE USED TO SCALE THE PLOT.

THE FILTER DELAY=0.960 TIMES THE ANTENNA SEPARATION



X-SCALE: "*"= 0.200E 02 UNITS

Y-SCALE: "*"= 0.900E 00 UNITS

THE TIME OF OCCURANCE OF THE CENTER OF THE MAIN LOBE IS 417.50.

THE WIDTH OF THE MAIN LOBE IS 83.00.

THE LEADING EDGE OF THE MAIN LOBE OCCURS AT 376.00.

FIGURE 3-14

THE FOLLOWING DATA IS FOR A NEW ANGLE OF ARRIVAL.

ANGLE OF ARRIVAL= 60.0...THIS FILTER IS MATCHED TO 60.7.

TIME IS PLOTTED ALONG THE X-AXIS AND THE FILTER OUTPUT IS PLOTTED ALONG THE Y-AXIS........DISREGARD 0.0/0.0 AND 1600.0/48.0THEY ARE USED TO SCALE THE PLOT.

THE FILTER DELAY=0.980 TIMES THE ANTENNA SEPARATION

X-SCALE: "*"= 0.200E 02 UNITS

Y-SCALE: "*"= 0.900E 00 UNITS

THE TIME OF OCCURANCE OF THE CENTER OF THE MAIN LOBE IS 417.50.

THE WIDTH OF THE MAIN LOBE IS 83.00.

THE LEADING EDGE OF THE MAIN LOBE OCCURS AT 376.00.

FIGURE 3-15

THE FOLLOWING DATA IS FOR A NEW ANGLE OF ARRIVAL.

ANGLE OF ARRIVAL= 60.0...THIS FILTER IS MATCHED TO 60.0.

TIME IS PLOTTED ALONG THE X-AXIS AND THE FILTER
OUTPUT IS PLOTTED ALONG THE Y-AXIS........DISREGARD
0.0/0.0 AND 1600.0/48.0THEY ARE USED TO SCALE THE
PLOT.

THE FILTER DELAY=1.000 TIMES THE ANTENNA SEPARATION

X-SCALE: "*"= 0.200E 02 UNITS

Y-SCALE: "*"= 0.800E 00 UNITS

THE TIME OF OCCURANCE OF THE CENTER OF THE MAIN LOBE IS 425.00.

THE WIDTH OF THE MAIN LOBE IS 100.00.

THE LEADING EDGE OF THE MAIN LOBE OCCURS AT 375.00.

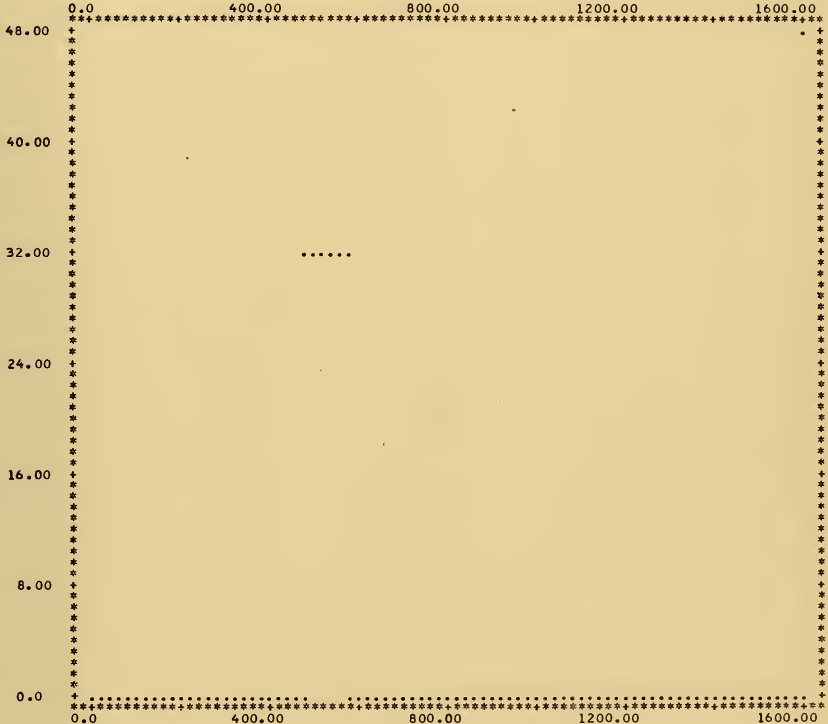
FIGURE 3-16

THE FOLLOWING DATA IS FOR A NEW ANGLE OF ARRIVAL.

ANGLE OF ARRIVAL= 50.0...THIS FILTER IS MATCHED TO 50.0.

TIME IS PLOTTED ALONG THE X-AXIS AND THE FILTER OUTPUT IS PLOTTED ALONG THE Y-AXIS........DISREGARD 0.0/0.0 AND 1600.0/48.0THEY ARE USED TO SCALE THE PLOT.

THE FILTER DELAY=1.000 TIMES THE ANTENNA SEPARATION



X-SCALE: "*"= 0.200E 02 UNITS

Y-SCALE: "*"= 0.800E 00 UNITS

THE TIME OF OCCURANCE OF THE CENTER OF THE MAIN LOBE IS 529.99.

THE WIDTH OF THE MAIN LOBE IS 100.00.

THE LEADING EDGE OF THE MAIN LOBE OCCURS AT 479.99.

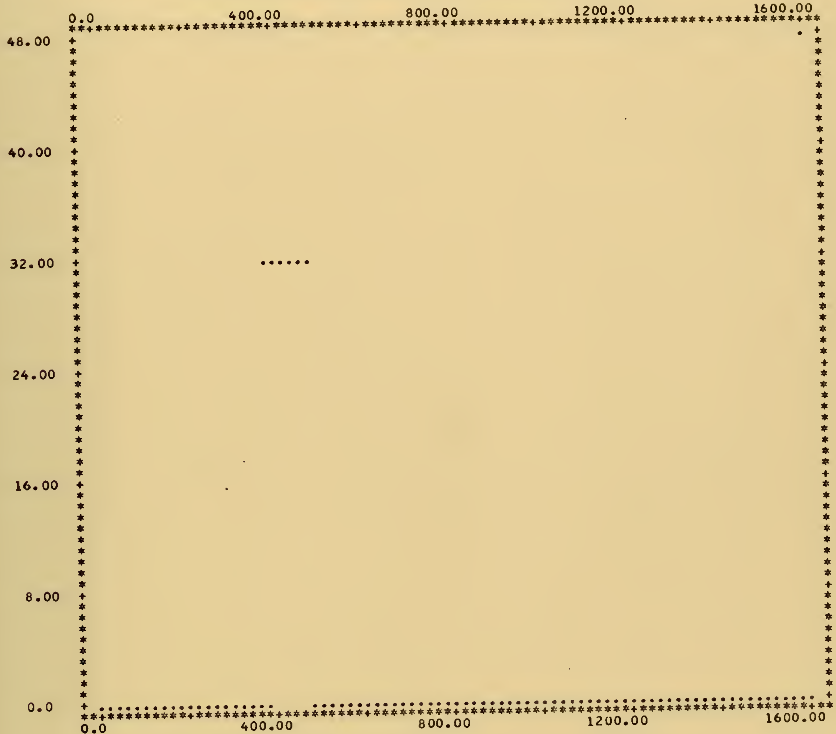
FIGURE 3-17

THE FOLLOWING DATA IS FOR A NEW ANGLE OF ARRIVAL.

ANGLE OF ARRIVAL= 60.0...THIS FILTER IS MATCHED TO 60.0.

TIME IS PLOTTED ALONG THE X-AXIS AND THE FILTER
OUTPUT IS PLOTTED ALONG THE Y-AXIS........DISREGARD
0.0/0.0 AND 1600.0/48.0THEY ARE USED TO SCALE THE
PLOT.

THE FILTER DELAY=1.000 TIMES THE ANTENNA SEPARATION



X-SCALE: "*"= 0.200E 02 UNITS

Y-SCALE: "*"= 0.800E 00 UNITS

THE TIME OF OCCURANCE OF THE CENTER OF THE MAIN LOBE IS 425.00.

THE WIDTH OF THE MAIN LOBE IS 100.00.

THE LEADING EDGE OF THE MAIN LOBE OCCURS AT 375.00.

FIGURE 3-18

THE FOLLOWING DATA IS FOR A NEW ANGLE OF ARRIVAL.

ANGLE OF ARRIVAL= 70.0...THIS FILTER IS MATCHED TO 70.0.

TIME IS PLOTTED ALONG THE X-AXIS AND THE FILTER OUTPUT IS PLOTTED ALONG THE Y-AXIS........DISREGARD 0.0/0.0 AND 1600.0/48.0THEY ARE USED TO SCALE THE PLOT.

THE FILTER DELAY=1.000 TIMES THE ANTENNA SEPARATION

X-SCALE: "*"= 0.200E 02 UNITS

Y-SCALE: "*"= 0.800E 00 UNITS

THE TIME OF OCCURANCE OF THE CENTER OF THE MAIN LOBE IS 305.00.

THE WIDTH OF THE MAIN LOBE IS 100.00.

THE LEADING EDGE OF THE MAIN LOBE OCCURS AT 255.00.

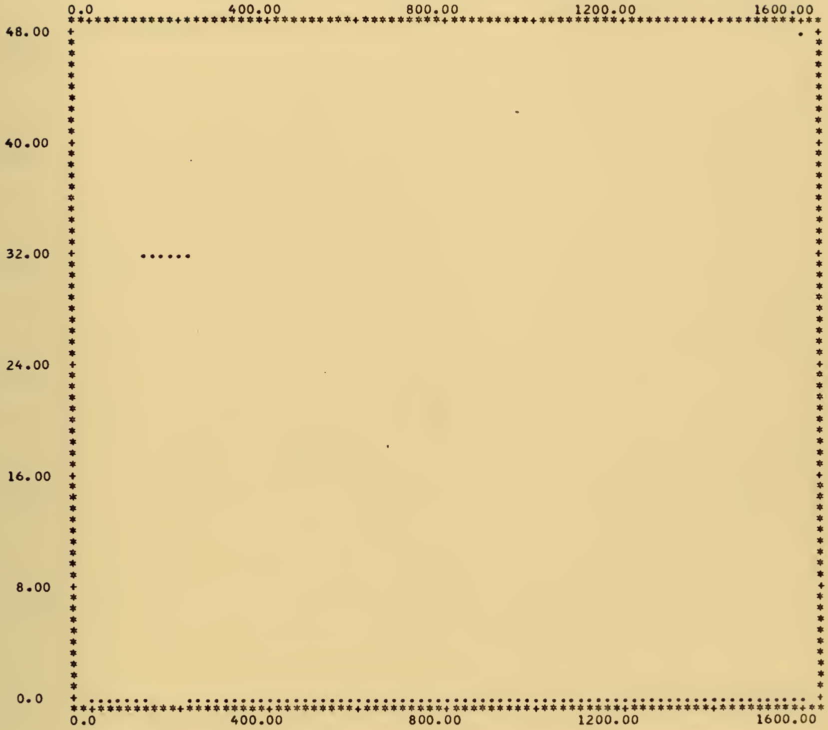
FIGURE 3-19

THE FOLLOWING DATA IS FOR A NEW ANGLE OF ARRIVAL.

ANGLE OF ARRIVAL= 80.0...THIS FILTER IS MATCHED TO 80.0.

TIME IS PLOTTED ALONG THE X-AXIS AND THE FILTER OUTPUT IS PLOTTED ALONG THE Y-AXIS.......DISREGARD 0.0/0.0 AND 1600.0/48.0THEY ARE USED TO SCALE THE PLOT.

THE FILTER DELAY=1.000 TIMES THE ANTENNA SEPARATION



X¬SCALE: "*"= 0.200E 02 UNITS

Y-SCALE: "*"= 0.800E 00 UNITS

THE TIME OF OCCURANCE OF THE CENTER OF THE MAIN LOBE IS 170.00.

THE WIDTH OF THE MAIN LOBE IS 100.00.

THE LEADING EDGE OF THE MAIN LOBE OCCURS AT 120.00.

FIGURE 3-20

THE FOLLOWING DATA IS FOR A NEW ANGLE OF ARRIVAL.

ANGLE OF ARRIVAL= 90.0...THIS FILTER IS MATCHED TO 90.0.

TIME IS PLOTTED ALONG THE X-AXIS AND THE FILTER
OUTPUT IS PLOTTED ALONG THE Y-AXIS........DISREGARD
0.0/0.0 AND 1600.0/48.0THEY ARE USED TO SCALE THE
PLOT.

THE FILTER DELAY=1.000 TIMES THE ANTENNA SEPARATION

X-SCALE: "*"= 0.200E 02 UNITS

Y-SCALE: "*"= 0.800E 00 UNITS

THE TIME OF OCCURANCE OF THE CENTER OF THE MAIN LOBE IS 50.00.

THE WIDTH OF THE MAIN LOBE IS 100.00.

THE LEADING EDGE OF THE MAIN LOBE OCCURS AT 0.0 .

FIGURE 3-21

this is a true statement it is not the criterion utilized for AOA determination. The disadvantage of this method of establishing the AOA is the requirement that the signal have a sharply discernible modulation event. An unmatched autocorrelation output will usually have an output which exceeds twice the code length, 32 in this case, at some time in the correlation process. This was also rejected as a method of determining the exact match case since this event generally had an extremely short time duration. Therefore the autocorrelation output is only utilized to provide information concerning the signal and the associated modulation. The cross-correlation output establishes the AOA and is required to indicate which autocorrelation output is correct for the true determined AOA.

2. Cross-Correlation Results

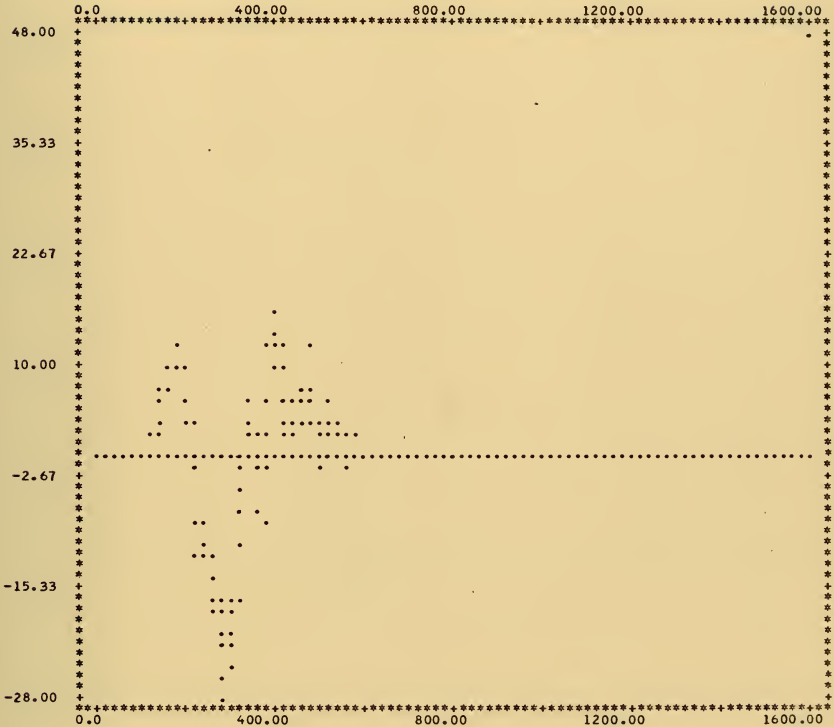
The program was processed utilizing the signal and the system parameters discussed for the autocorrelation process. The changing of one control card in the data deck is all that is required to shift the program from autocorrelation to cross-correlation. Figure 3-22 is a plot of a completely mismatched case. The expected output for the matched case is zero for all time. As can be seen from the plot for this case the output is not zero. Figure 3-23 to 3-27 are output from conditions where the delay is more closely aligned to the required matched case. Even though the filter (correlator) is more closely matched to the correct delay a null value cannot be seen to be rapidly

THE FOLLOWING DATA IS FOR A NEW ANGLE OF ARRIVAL.

ANGLE OF ARRIVAL= 60.0...THIS FILTER IS MATCHED TO 72.6.

TIME IS PLOTTED ALONG THE X-AXIS AND THE FILTER
OUTPUT IS PLOTTED ALONG THE Y-AXIS........DISREGARD
0.0/0.0 AND 1600.0/48.0THEY ARE USED TO SCALE THE
PLOT.

THE FILTER DELAY=0.600 TIMES THE ANTENNA SEPARATION



X-SCALE: "*"= 0.200E 02 UNITS

Y-SCALE: "*"= 0.127E 01 UNITS

THE TIME OF OCCURANCE OF THE CENTER OF THE MAIN LOBE IS 0.0 .

THE WIDTH OF THE MAIN LOBE IS 0.0 .

THE LEADING EDGE OF THE MAIN LOBE OCCURS AT 0.0 .

FIGURE 3-22

THE FOLLOWING DATA IS FOR A NEW ANGLE OF ARRIVAL.

ANGLE OF ARRIVAL= 60.0...THIS FILTER IS MATCHED TO 63.3.

TIME IS PLOTTED ALONG THE X-AXIS AND THE FILTER OUTPUT IS PLOTTED ALONG THE Y-AXIS........DISREGARD 0.0/0.0 AND 1600.0/48.0THEY ARE USED TO SCALE THE PLOT.

THE FILTER DELAY=0.900 TIMES THE ANTENNA SEPARATION

X-SCALE: "*"= 0.200E 02 UNITS

Y-SCALE: "*"= 0.103E 01 UNITS

THE TIME OF OCCURANCE OF THE CENTER OF THE MAIN LOBE IS 0.0 .

THE WIDTH OF THE MAIN LOBE IS 0.0 .

THE LEADING EDGE OF THE MAIN LOBE OCCURS AT 0.0 .

FIGURE 3-23

THE FOLLOWING DATA IS FOR A NEW ANGLE OF ARRIVAL.

ANGLE OF ARRIVAL= 60.0...THIS FILTER IS MATCHED TO 62.6.

TIME IS PLOTTED ALONG THE X-AXIS AND THE FILTER OUTPUT IS PLOTTED ALONG THE Y-AXIS........DISREGARD 0.0/0.0 AND 1600.0/48.0THEY ARE USED TO SCALE THE PLOT.

THE FILTER DELAY=0.920 TIMES THE ANTENNA SEPARATION

X-SCALE: "*"= 0.200E 02 UNITS

Y-SCALE: "*"= 0.100E 01 UNITS

THE TIME OF OCCURANCE OF THE CENTER OF THE MAIN LOBE IS 0.0 .

THE WIDTH OF THE MAIN LOBE IS 0.0 .

THE LEADING EDGE OF THE MAIN LOBE OCCURS AT 0.0 .

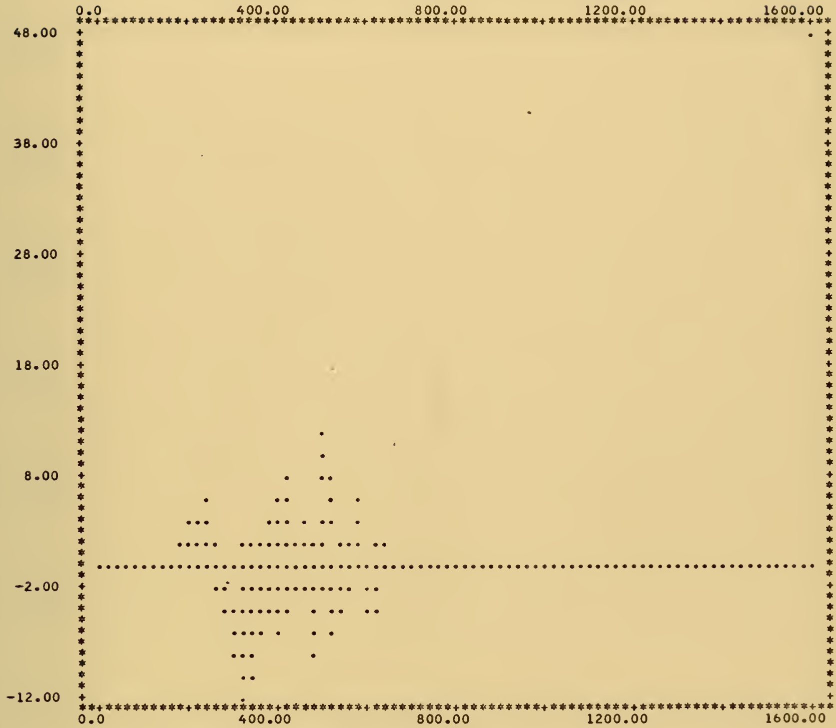
FIGURE 3-24

THE FOLLOWING DATA IS FOR A NEW ANGLE OF ARRIVAL.

ANGLE OF ARRIVAL= 60.0...THIS FILTER IS MATCHED TO 62.0.

TIME IS PLOTTED ALONG THE X-AXIS AND THE FILTER
OUTPUT IS PLOTTED ALONG THE Y-AXIS.......DISREGARD
0.0/0.0 AND 1600.0/48.0THEY ARE USED TO SCALE THE
PLOT.

THE FILTER DELAY=0.940 TIMES THE ANTENNA SEPARATION



X-SCALE: "*"= 0.200E 02 UNITS

Y-SCALE: "*"= 0.100E 01 UNITS

THE TIME OF OCCURANCE OF THE CENTER OF THE MAIN LOBE IS 0.0 .

THE WIDTH OF THE MAIN LOBE IS 0.0 .

THE LEADING EDGE OF THE MAIN LOBE OCCURS AT 0.0 .

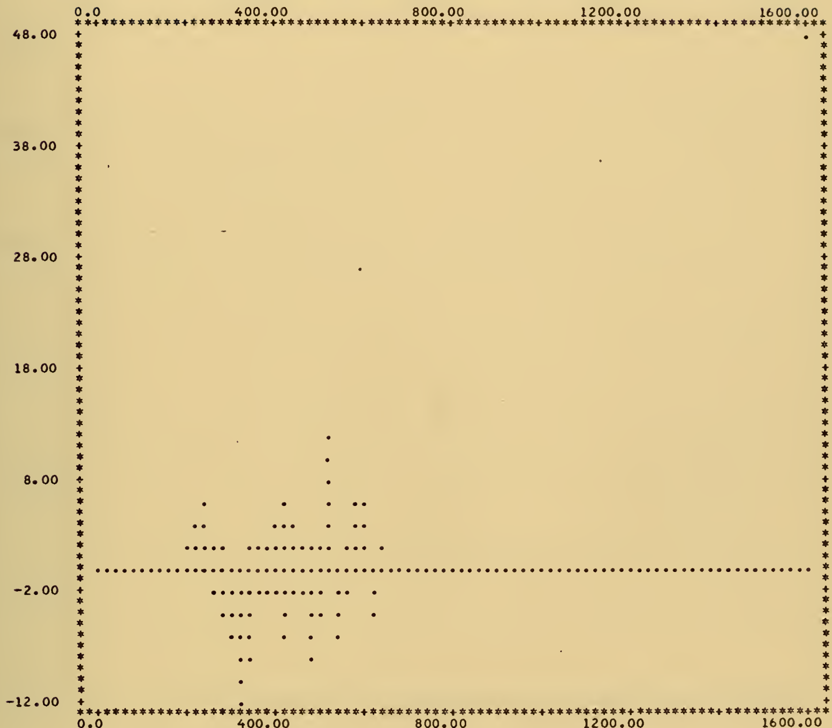
FIGURE 3-25

THE FOLLOWING DATA IS FOR A NEW ANGLE OF ARRIVAL.

ANGLE OF ARRIVAL= 60.0...THIS FILTER IS MATCHED TO 61.3.

TIME IS PLOTTED ALONG THE X-AXIS AND THE FILTER OUTPUT IS PLOTTED ALONG THE Y-AXIS........DISREGARD 0.0/0.0 AND 1600.0/48.0THEY ARE USED TO SCALE THE PLOT.

THE FILTER DELAY=0.960 TIMES THE ANTENNA SEPARATION



X-SCALE: "*"= 0.200E 02 UNITS

Y-SCALE: "*"= 0.100E 01 UNITS

THE TIME OF OCCURANCE OF THE CENTER OF THE MAIN LOBE IS 0.0 .

THE WIDTH OF THE MAIN LOBE IS 0.0 .

THE LEADING EDGE OF THE MAIN LOBE OCCURS AT 0.0 .

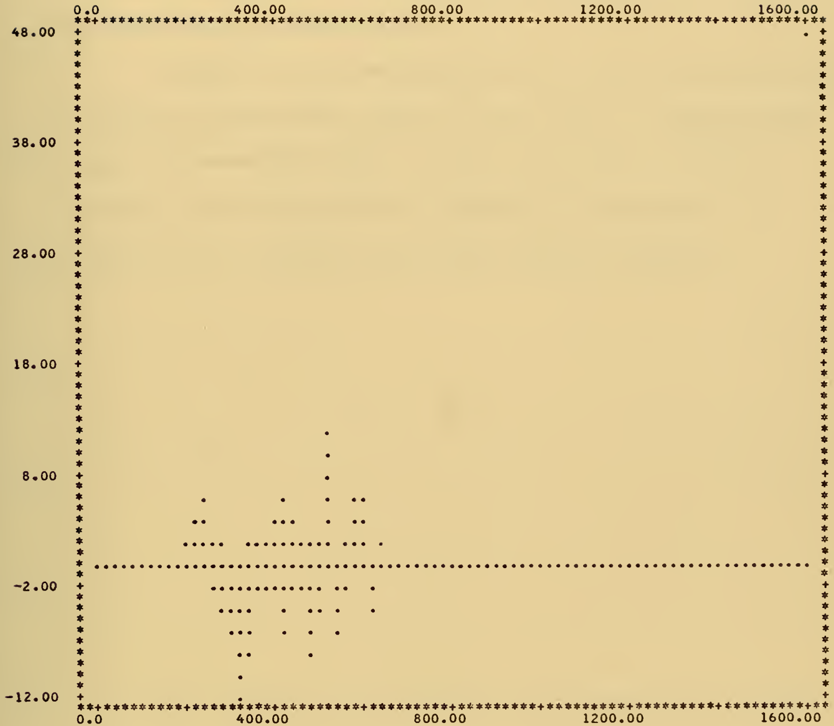
FIGURE 3-26

THE FOLLOWING DATA IS FOR A NEW ANGLE OF ARRIVAL.

ANGLE OF ARRIVAL= 60.0...THIS FILTER IS MATCHED TO 60.7.

TIME IS PLOTTED ALONG THE X-AXIS AND THE FILTER
OUTPUT IS PLOTTED ALONG THE Y-AXIS........DISREGARD
0.0/0.0 AND 1600.0/48.0THEY ARE USED TO SCALE THE
PLOT.

THE FILTER DELAY=0.980 TIMES THE ANTENNA SEPARATION



X-SCALE: "*"= 0.200E 02 UNITS

Y-SCALE: "*"= 0.100E 01 UNITS

THE TIME OF OCCURANCE OF THE CENTER OF THE MAIN LOBE IS 0.0 .

THE WIDTH OF THE MAIN LOBE IS 0.0 .

THE LEADING EDGE OF THE MAIN LOBE OCCURS AT 0.0 .

FIGURE 3-27

approaching as the delay approaches the correct value. The correct value is indicated on the plot for X.XXX equal to 1.000 in the statement just above the plot. The exact case is shown in figure 3-28. This zero output is so unique and dramatic that it was chosen as the criterion to establish the exact AOA.

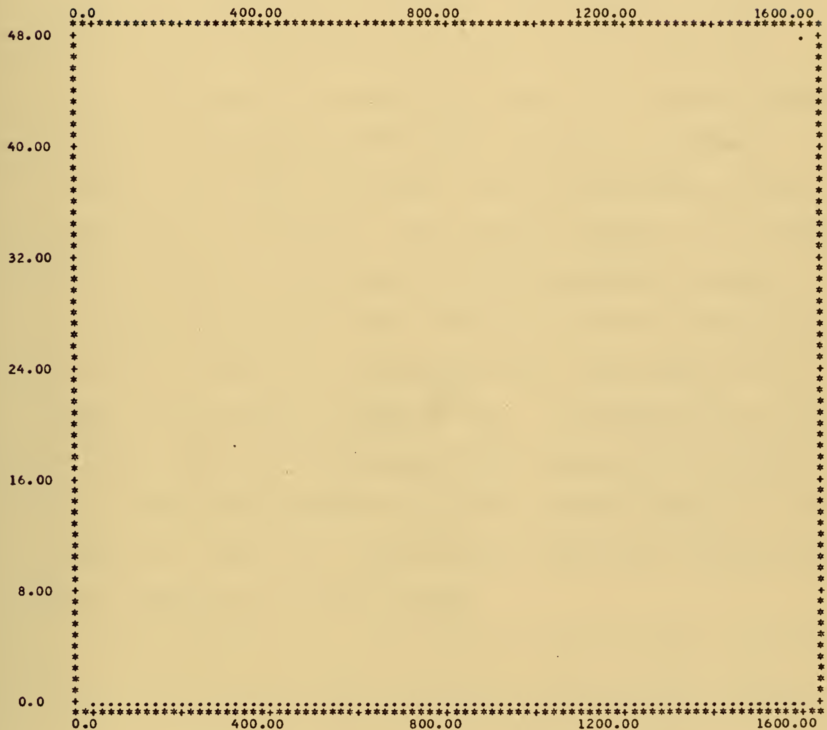
Since the autocorrelation and the cross-correlation outputs are processed from the same set of tapped delay lines for each AOA then as soon as the zero output is located the autocorrelation output of the signal is available for further processing and/or analysis.

THE FOLLOWING DATA IS FOR A NEW ANGLE OF ARRIVAL.

ANGLE OF ARRIVAL= 60.0...THIS FILTER IS MATCHED TO 60.0.

TIME IS PLOTTED ALONG THE X-AXIS AND THE FILTER
OUTPUT IS PLOTTED ALONG THE Y-AXIS........DISREGARD
0.0/0.0 AND 1600.0/48.0THEY ARE USED TO SCALE THE
PLOT.

THE FILTER DELAY=1.000 TIMES THE ANTENNA SEPARATION



X-SCALE: "*"= 0.200E 02 UNITS

Y-SCALE: "*"= 0.800E 00 UNITS

THE TIME OF OCCURANCE OF THE CENTER OF THE MAIN LOBE IS 0.0 .

THE WIDTH OF THE MAIN LOBE IS 0.0 .

THE LEADING EDGE OF THE MAIN LOBE OCCURS AT 0.0 .

FIGURE 3-28

IV. SUMMARY AND RECOMMENDATIONS

A. SUMMARY

The problem of determining the angle-of-arrival of a propagating radio wave has been investigated from the viewpoint of simplifying the antenna system required while retaining the inherent accuracy of a complex antenna system. The technique arrived at utilized the phase coding of the received signal and the processing of this signal for two outputs. The required outputs are a pseudo autocorrelation output and a cross-correlation output.

The realization of AOA information and the simultaneous ability to recover an autocorrelation type output of the signal is detailed in chapter III. In addition to the DF and the intercept information this technique also results in a simple configuration from the antenna location to the processor, namely two transmission lines vice the multiple lines required by other systems.

The accuracy of a DF system has historically resided in the ability to produce either a large complex antenna system or the wide separation of simple antennas or in some cases a little of each. The technique described in this investigation requires simple antennas in a simple configuration. Additionally the antenna system is stationary.

The number of antennas is determined by the code length desired. The code length is chosen in accordance with the desired correlation gain and the physical environment. The correlation gain is equal to twice the code length.

The bearing accuracy or resolution ability is a direct function of the incremental steps in the delay lines. That is if the delay lines are matched in delay to one degree increments then the resolution of the system is one degree. If the delay lines are in increments of half a degree then the system will resolve lines of bearing to half a degree. Therefore the resolution ability is limited by the ability to physically produce these lines in the increments desired.

This technique will produce ambiguous AOA data since the system can only uniquely determine AOA data in a 180 degree sector. The data in the mirror image 180 degree sector can be confirmed (or discarded) by a simple auxiliary antenna sampling signal strength. Therefore the ambiguity can be resolved.

A digital computer model was utilized to show that there are no ambiguous angle-of-arrivals in the 180 degree sector. The model also verified that the resolving ability of the system was only a function of the ability to physically realize the appropriate delay lines.

B. CONCLUSIONS

The ability to determine the angle-of-arrival of an incoming signal was shown to be a processing function

utilizing a relatively simple antenna arrangement. Ambiguities could be resolved and the resolution ability of the system was not limited by the theory presented but rather is a function of physically realizable hardware.

C. RECOMMENDATIONS FOR FURTHER INVESTIGATION

1. A simple antenna system, signal encoder, delay lines and receiver should be built and data taken to verify the computer model results. A four antenna group, simple encoder, delay lines for thirty degree steps and any available receiver could be utilized. The frequency chosen should be low enough such that phase lengths are not a problem, but not so low as to require extreme spacing between antennas in order to reduce mutual coupling. A frequency in the region of 200 to 300 MHz would probably suffice.

2. A study should be made to attempt to reduce the number and/or precision required for the tapped delay lines.

3. A study should be made to determine parameters required for the optimum performance utilizing the simplest antenna. The same study should undertake the determination of the optimum performance to be obtained by utilizing more than one simple antenna system in various configurations.

4. An investigation should be made of a means to negate the error due to a non-zero elevation angle of an incoming signal.

APPENDIX

COMPUTER PROGRAM

The computer simulation is a digital program written in FORTRAN IV level G. It was processed by an IBM 360/67 system and the built in functions are those normally available on this system.

The program requires a data deck input for the specific complementary code used in addition to the parameters required to process the code. The following words are peculiar to this program.

CODE1: First sequence in a complementary code.

CODE2: Second sequence in a complementary code.

SIGN: Summation sign, used for addition of correlator outputs

DELDEG: Incremental angle shift in degrees, used to obtain a new value for the angle.

START: The starting value in degrees of the incoming signal.

STOP: The final value in degrees of the incoming signal.

START-T: The starting time for the computation.

STOP-T: The completion time for the computation.

DSTEP: Incremental step for the parameter D, used to obtain a new value for the filter (correlator) delay.

NRANTS: The number of antennas in use.

SPACE: Spacing between antennas; antennas have uniform spacing.

DELT: Computation time increment.

TIMES: Multiplying factor used in the subprograms in order to utilize integer arithmetic and logic.

JJ: Control for surpressing data printout; do not print if JJ=2.

JJJ: Control for correlation function; if JJJ=1 then cross-correlate, if not then autocorrelate.

JJJJ: Control to surpress the final plot which is a summary of maximum amplitude versus angle; if JJJJ=2 then do not plot.

The data deck must be assembled in a specific sequence in order to have the program operate properly. Additionally if the data is not known a card must still be loaded into the data deck in order not to invalidate the read instructions. The data must be provided whether valid or not. The data cards are assembled as in figure A-1. The first card in the data deck is CODE1 and the last is JJJJ. All data cards are punched starting in column one. CODE1 and CODE2 are formated floating point F4.1 and each card can have up to eighteen entries. Each code is read from one card, if longer codes (greater than 18) are required then the read statement must be changed to read more than one card for each code. NRANTS, JJ, JJJ and

TYPICAL DATA DECK

```
1.0 1.0 1.0-1.0 1.0 1.0-1.0 1.0 1.0 1.0 1.0-1.0-1.0-1.0 1.0-1.0
1.0 1.0 1.0-1.0 1.0 1.0-1.0 1.0-1.0-1.0-1.0 1.0 1.0 1.0-1.0 1.0
  1.000000
  3.000000
  0.990000
 60.000000
 60.000000
  0.000000
  0.001000
        16
         2
         2
         2


CARD 1....FIRST SEQUENCE OF THE CODE PAIR.....(CODE1)
CARD 2....SECOND SEQUENCE OF THE CODE PAIR....(CODE2)
CARD 3....SUMMATION SIGN......................(SIGN)
CARD 4....ANGLE STEP..........................(DELDEG)
CARD 5....FILTER DELAY STARTING VALUE.........(D)
CARD 6....ANGLE START.........................(START)
CARD 7....ANGLE STOP..........................(STOP)
CARD 8....COMPUTATION TIME START..............(START-T)
CARD 9....FILTER DELAY STEP...................(DSTEP)
CARD 10...NUMBER OF ANTENNAS..................(NRANTS)
CARD 11...CONTROL FOR DATA PRINT..............(JJ)
CARD 12...CONTROL FOR TYPE OF CORRELATION.....(JJJ)
CARD 13...CONTROL FOR OUTPUT VS ANGLE PLOT....(JJJJ)
```

FIGURE A-1

JJJJ are formated in integer I11 all other data cards are formated in floating point F11.6.

The program is set up to provide for a pulse signal input with the pulse duration equal to twice the delay due to antenna separation. The program will automatically scale the built in pulse duration (W) and the antenna separation (SPACE) to accommodate any code length. Additionally the computation time is automatically scaled in order to include all the correlation outputs greater than zero and also provide for the maximum number of computations per angle and filter delay setting. The maximum number of computation intervals for a fixed angle and delay is 2000. The codes are read into computer memory and all necessary operations are accomplished in order to provide the proper autocorrelation and cross-correlation functions as a function of time, angle and filter delay. If data is provided which is beyond the array storage set aside for the computation then the program will attempt adjustments in the size of the data. After twenty attempts with no success the program will terminate and print out: DATA EXCEEDS ARRAY STORAGE... JOB TERMINATED.

The program will input all parameters, compute other required parameters in accordance with the inputted parameters, compute an output for a fixed time, angle and delay and then step the time variable to the next increment. After the time variable has been stepped across its range

the angle variable is incremented to a new value and the output is computed for all time values as the time variable is again swept through its range. After the angle variable has been swept through its range the delay variable is incremented to a new value. The output is then computed across the time range and the angle range. This sequence is followed until the full range of values for the delay variable have been used. In this manner the outputs of the filters (correlator outputs) are computed for all times of interest, all angles of interest and all desired variations of the filter delay lines.

The output available from this program is a plot routine of amplitude versus time for each and every value of angle and filter delay required. Additionally as shown in figure A-2 and A-3 several important statements are printed. The statements below the plot are valid and useful only for the matched autocorrelation condition where D=1.00. The data in these statements can be used for the autocorrelation unmatched case to roughly locate the pulse shape as the variable D approaches unity. After all values have been computed for the full range of time and angle variables and prior to the stepping of the variable D a summary plot of maximum amplitude versus angle and a table of this data can be plotted by selection of the proper control card.

A listing of important parameters and statements concerning the interpretation of the various control

commands are printed at the beginning of each computer run to aid in analysis of the data and the plots.

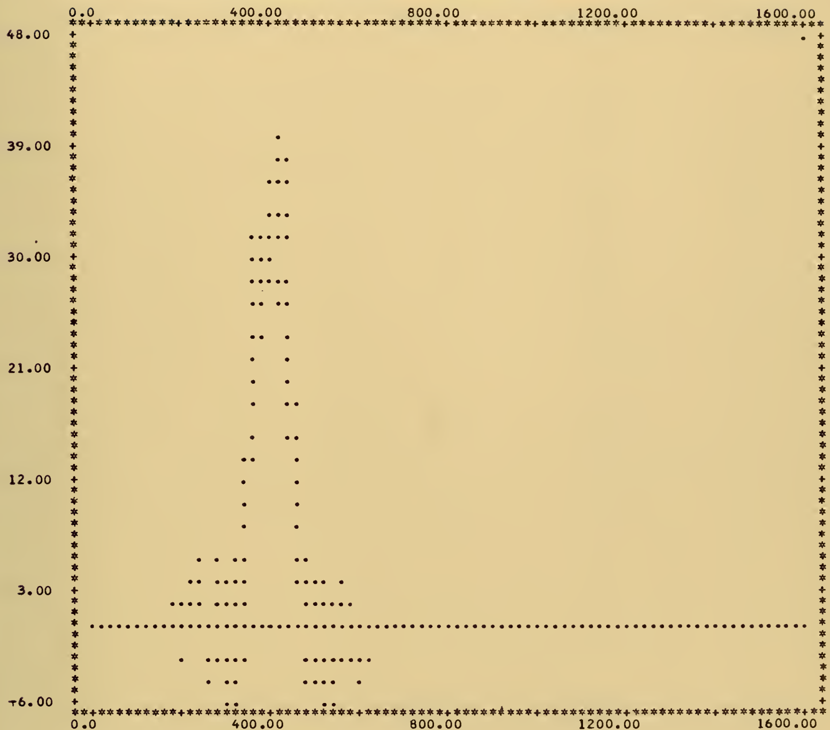
The maximum core size is 150K and due to the fine grain computation required by the program execution time for most investigations is in the 15 to 20 minute region.

THE FOLLOWING DATA IS FOR A NEW ANGLE OF ARRIVAL.

ANGLE OF ARRIVAL= 60.0...THIS FILTER IS MATCHED TO 63.3.

TIME IS PLOTTED ALONG THE X-AXIS AND THE FILTER
OUTPUT IS PLOTTED ALONG THE Y-AXIS........DISREGARD
0.0/0.0 AND 1600.0/48.0THEY ARE USED TO SCALE THE
PLOT.

THE FILTER DELAY=0.900 TIMES THE ANTENNA SEPARATION



X-SCALE: "*"= 0.200E 02 UNITS

Y-SCALE: "*"= 0.900E 00 UNITS

THE TIME OF OCCURANCE OF THE CENTER OF THE MAIN LOBE IS 401.00.

THE WIDTH OF THE MAIN LOBE IS 68.00.

THE LEADING EDGE OF THE MAIN LOBE OCCURS AT 367.00.

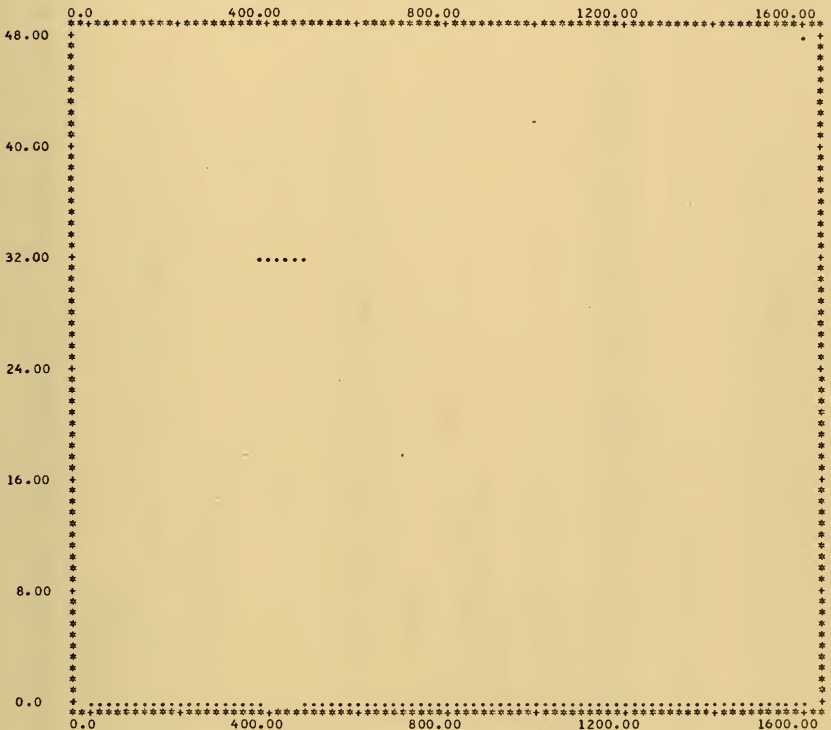
FIGURE A-2

THE FOLLOWING OATA IS FOR A NEW ANGLE OF ARRIVAL.

ANGLE OF ARRIVAL= 60.0...THIS FILTER IS MATCHEO TO 60.0.

TIME IS PLOTTED ALONG THE X-AXIS AND THE FILTER
OUTPUT IS PLOTTED ALONG THE Y-AXIS........DISREGARD
0.0/0.0 AND 1600.0/48.0THEY ARE USED TO SCALE THE
PLOT.

THE FILTER DELAY=1.000 TIMES THE ANTENNA SEPARATION



X-SCALE: "*"= 0.200E 02 UNITS

Y-SCALE: "*"= 0.800E 00 UNITS

THE TIME OF OCCURANCE OF THE CENTER OF THE MAIN LOBE IS 425.00.

THE WIDTH OF THE MAIN LOBE IS 100.00.

THE LEADING EDGE OF THE MAIN LOBE OCCURS AT 375.00.

FIGURE A-3

PHASE CODED DIRECTION FINDING SYSTEM SIMULATION UTILIZING COMPLEMENTARY CODES

```
      COMMON/ZZZ/ADD(2000)
      COMMON/AAA/ADD1(2000)
      COMMON/BBB/ADD2(2000)
      COMMON/RRR/TA(200),TOUT(200),SUM(50),CODE1(18),CODE2(18),
     1PT(2000),POUT(2000),KDUMB(18),JDUMB(18),TIME(400),
     2IDUMB(18),SIG(50)
      REAL*4 IDUMB,JDUMB,KDUMB
      INTEGER*4 T3,FIL3,DELT3,W3,D3
      DO 7 I=1,18
      CODE1(I)=0.0
      CODE2(I)=0.0
      JDUMB(I)=0.0
      KDUMB(I)=0.0
    7 CONTINUE
C
C
C     READ IN CODES FROM CARDS,EACH CARD CAN HAVE UP TO 18 ENTRIES
C
C
      READ(5,8) CODE1,CODE2
    8 FORMAT(18F4.1)
      WRITE(6,11)
   11 FORMAT (///T56,'CODE 1',//)
      WRITE(6,9) (CODE1(I),I=1,18)
    9 FORMAT (//2X,18F6.1)
      WRITE (6,13)
   13 FORMAT (///T56,'CODE 2',//)
      WRITE(6,12) (CODE2(I),I=1,18)
   12 FORMAT (//2X,18F6.1)
      WRITE (6,106)
  106 FORMAT(//////T7,'DELT',T15,'TIMES',T27,'SIGN',T37,'DELDEG',T49,
     1'W',T59,'D',T67,'DSTEP',T76,'START',T87,'STOP',T97,'SPACE',T104,
     2'NRANTS',T112,'START-T',T122,'STOP-T',//)
C
C
C     DELT=COMPUTATION INTERVAL
C
      DELT=0.001
C
C
C     READ IN CONSTANTS FROM CARDS IN THE FOLLOWING ORDER,
C     SIGN,DELDEG,D,START,STOP,START-T,DSTEP,NRANTS.
C
C
      READ (5,100) SIGN,DELDEE,D,STARR,STOO,GO,DSTEP
```

```
  100 FORMAT (F11.6)
      READ (5,105) NRANTS,JJ,JJJ,JJJJ
  105 FORMAT (I11)
C
C
C     SIGN=SUMMATION SIGN FOR ARRAY,SIGN=1...ADD,SIGN=-1...SUBTRACT
C     DELDEG=SHIFT IN ANGLE OF INCOMING SIGNAL..IN DEGREES
C     D=INDEX TO VARY THE PHASE SHIFT OF THE DELAY LINES IN THE FILTER
C        IF D=1,THEN THE DELAY IN THE FILTER=THE ANTENNA SEPERATION
C     START=THE STARTING VALUE IN DEGREES OF THE INCOMING SIGNAL
C     E.G. A SIGNAL COLINEAR WITH THE LINE OF THE ARRAY=0.0 DEGREES.
C     STOP=THE FINAL VALUE IN DEGREES OF THE INCOMING SIGNAL
C     START-T=TIME TO START COMPUTATION,E.G. T=0.0
C     DSTEP=COMPUTATION INTERVAL FOR THE PARAMETER D.
C     JJ= CONTROL FOR PRINTING TABULATION OF DATA(TIME,OUTPUT-A,
C     OUTPUT-B,FILTER OUTPUT,ANGLE)...IF JJ=2...DO NOT PRINT...
C     JJJ=CONTROL FOR AUTOCORRELATION OR CROSSCORRELATION..IF JJJ=1 THEN
C     CROSSCORRELATE...IF NOT EQUAL TO ONE,E.G. JJJ=2 THEN AUTOCORRELATE
C     JJJJ=CONTROL TO PLOT MAX FILTER OUTPUT VERSES ANGLE..
C     IF JJJJ=2 THEN SKIP THIS PLOT..
C     NRANTS=NUMBER OF INDIVIDUAL ANTENNAS IN EACH ROW
C
C     COMPUTE W,SPACE,STOP-T AND TIMES IAW CODE LENGTH.
C
C
      STOP=STOO*0.017453
      START=STARR*0.017453
      DELDEG=DELDEE*0.017453
      SPACE=0.1
      W=0.2
      JHALT=1
 2222 HALT=(2.0*(SPACE*(NRANTS-1)))+W
      CHECK=HALT/DELT
      IF(CHECK.LT.2000.0) GO TO 4444
      SPACE=SPACE/2.0
      W=W/2.0
      JHALT=JHALT+1
      IF (JHALT.EQ.20) GO TO 4000
         GO TO 2222
 4444 TIMES=1.0/DELT
C
C
C     W=LENGTH (DURATION) OF THE INCOMING SIGNAL
C     SPACE=ANTENNA SEPERATION,ANTENNAS HAVE UNIFORM SPACING
C     STOP-T=TIME TO STOP COMPUTATION,E.G. T=16.0
C     TIMES=MULTIPLYING FACTOR USED IN SUB-PROGRAMS.
C
C
```

```
      WRITE (6,200) DELT,TIMES,SIGN,DELDEE,W,D,DSTEP,STARR,STOO,SPACE,
     1NRANTS,GO,HALT
  200 FORMAT (' ',10F10.4,I5,F13.3,F9.3,/)
      IF (JJ.EQ.2) GO TO 601
      WRITE (6,603)
  603 FORMAT (///T20,'PRINT DATA',//)
      GO TO 605
  601 WRITE (6,602)
  602 FORMAT (///T20,'DO NOT PRINT DATA',//)
  605 IF (JJJ.EQ.1) GO TO 606
      WRITE (6,604)
  604 FORMAT (///T20,'PROCEEDING WITH AUTOCORRELATION',//)
      GO TO 608
  606 WRITE (6,607)
  607 FORMAT (///T20,'PROCEEDING WITH CROSSCORRELATION UTILIZING ',
     1'ORTHOGONAL COMPLEMENTARY SEQUENCES',//)
  608 IF (JJJJ.EQ.2) GO TO 610
      WRITE (6,609)
  609 FORMAT (///T20,'PLOT MAXIMUM FILTER OUTPUT VS ANGLE',//)
      GO TO 204
  610 WRITE (6,611)
  611 FORMAT (///T20,'DO NOT PLOT MAXIMUM FILTER OUTPUT VS ANGLE',//)
  204 WRITE (6,205)
  205 FORMAT (//'++++++Y+++++++++++++++++++++++++++++++++++++++++++++',
     1'++++++++++++++++++++++++++++++++++++++++++++++++Y+++++++++++++',/)
      IF (NRANTS.GT.12) GO TO 210
      AAAA=24.0
      GO TO 1
  210 IF (NRANTS.GT.20) GO TO 220
      AAAA=48.0
      GO TO 1
  220 AAAA=72.0
    1 ANGLE=START
      IC=0
      DO 16 I=1,2000
      ADD2(I)=0.0
      ADD1(I)=0.0
      ADD(I)=0.0
      PT(I)=0.0
      POUT(I)=0.0
   16 CONTINUE
      DO 17 I=1,400
      TIME(I)=0.0
   17 CONTINUE
      DO 4 I=1,200
      TA(I)=0.0
      TOUT(I)=0.0
    4 CONTINUE
```

```
C
C
C     START COMPUTATION WITH INITIAL OR NEW VALUE OF ANGLE OF ARRIVAL
C
C
    2 DELAY=SPACE*COS(ANGLE)
      FILTER=D*DELAY
      OUTMAX=0.0
      BRNG=ANGLE*57.2958
      T=GO
      K1=1
      KK=0
      DO 3 I=1,50
      SIG(I)=0.0
      SUM(I)=0.0
    3 CONTINUE
C
C
C     IC=COUNTER FOR PLOTP SUBPROGRAM...ANGLE VS AMPLITUDE
C
C
      IC=IC+1
      III=0
      IF (JJ.EQ.2) GO TO 6
      WRITE(6,1000)
 1000 FORMAT (//T12,'TIME',T24,'OUTPUT-A',T40,'OUTPUT-B',T52,
     1'FILTER OUTPUT',T72,'ANGLE',//)
C
C
C     START COMPUTATION AT THE INITIAL OR NEW TIME
C     M INDICATES THE CODE IN USE,M=1 INDICATES CODE 1 IN USE
C
C
    6 M=1
C
C
C     LOAD CODE 1 INTO THE DUMMY ARRAY
C
C
      DO 10 I=1,18
      IDUMB(I)=CODE1(I)
   10 CONTINUE
C
C
C     COMPUTE SIGNAL AT OUTPUT OF EACH INDIVIDUAL ANTENNA
C
C
      I=1
```

```
   15 SIG(I)=F(T,I,W,DELAY,TIMES)
      I=I+1
      IF(I.LE.NRANTS) GO TO 15
C
C
C     CODE ANTENNA OUTPUTS AND SUM
C
C
   19 K2=1
      ADD(K1)=IDUMB(K2)*SIG(K2)
      K2=K2+1
   20 ADD(K1)=ADD(K1)+IDUMB(K2)*SIG(K2)
      K2=K2+1
      IF (K2.LE.NRANTS) GO TO 20
      IF (M.GT.1) GO TO 21
      ADD1(K1)=ADD(K1)
      GO TO 22
   21 ADD2(K1)=ADD(K1)
C
C
C     COMPUTE SIGNALS AT THE OUTPUT OF EACH DELAY LINE IN THE FILTER
C
C
   22 J=1
   25 SUM(J)=G(T,J,FILTER,DELT,M,TIMES)
      J=J+1
      IF(J.LE.NRANTS) GO TO 25
      IF (JJJ.NE.1) GO TO 30
      IF (M.EQ.2) GO TO 29
C
C
C     GENERATE FILTER CODE FOR OUTPUT-A
C
C
      DO 28 I=1,18
      JDUMB(I)=-1.0*CODE2(I)
   28 CONTINUE
      GO TO 26
C
C
C     GENERATE FILTER CODE FOR OUTPUT-B
C
C
   29 DO 27 I=1,18
      JDUMB(I)=CODE1(I)
   27 CONTINUE
      GO TO 26
C
```

```
C
C     REVERSE THE CODE
C
C
   30 JK=1
      KDUMB(JK)=IDUMB(JK)
   37 JK=JK+1
      KDUMB(JK)=IDUMB(JK)
      IF (KDUMB(JK).NE.0.0) GO TO 37
      JKJ=JK-1
      DO 38 KJ=1,JKJ
      KKK=JK-KJ
      JDUMB(KJ)=KDUMB(KKK)
   38 CONTINUE
C
C
C     CODE DELAY LINE OUTPUTS AND SUM
C
C
   26 L=1
      OUTPUT=JDUMB(L)*SUM(L)
      L=L+1
   35 OUTPUT=OUTPUT+JDUMB(L)*SUM(L)
      L=L+1
      IF(L.LE.NRANTS) GO TO 35
      IF(M.GT.1) GO TO 55
      AOUT=OUTPUT
C
C
C     CALL UP CODE-2
C
C
      DO 45 I=1,18
      IDUMB(I)=CODE2(I)
   45 CONTINUE
      M=M+1
      GO TO 19
   55 BOUT=OUTPUT
C
C
C     SUM THE FILTER OUTPUTS...THIS IS THE FINAL OUTPUT
C
C
      SIGOUT=AOUT+SIGN*BOUT
   57 IF(SIGOUT.NE.(2*NRANTS)) GO TO 56
      III=III+1
      TIME(III)=T
C
```

```
C
C     KK=COUNTER FOR PLOTP SUBPROGRAM...TIME VS AMPLITUDE
C
C
   56 KK=KK+1
      PT(KK)=T*TIMES
      POUT(KK)=SIGOUT
      IF (JJ.EQ.2) GO TO 64
      WRITE (6,2000) T,AOUT,BOUT,SIGOUT,BRNG
 2000 FORMAT (' ',4F15.4,F15.1,/)
   64 IF(OUTMAX.GE.SIGOUT) GO TO 65
      OUTMAX=SIGOUT
   65 TOUT(IC)=OUTMAX
      TA(IC)=BRNG
      T=T+DELT
      K1=K1+1
      IF (T.LE.HALT) GO TO 6
      KK=KK+1
      PT(KK)=0.0
      POUT(KK)=0.0
      KK=KK+1
      PT(KK)=HALT*TIMES
      POUT(KK)=AAAA
      WRITE (6,2500)
 2500 FORMAT (//T30,'THE FOLLOWING DATA IS FOR A NEW ANGLE OF',
     1' ARRIVAL.'/)
      BBBB=ARCOS(D*COS(ANGLE))
      FILANG=BBBB/0.01745
      WRITE (6,2700) BRNG,FILANG
 2700 FORMAT (//T30,'ANGLE OF ARRIVAL=',F5.1,'...THIS FILTER IS ',
     1'MATCHED TO ',F5.1,'.',/)
      WRITE (6,2800) GO,PT(KK),AAAA
 2800 FORMAT (//T30,'TIME IS PLOTTED ALONG THE X-AXIS AND THE FILTER'/
     1T30,'OUTPUT IS PLOTTED ALONG THE Y-AXIS.......DISREGARD',/
     2T30,F4.1,'/0.0 AND ',F6.1,'/',F4.1,'THEY ARE USED TO SCALE THE',/
     3T30,'PLOT.'/)
      WRITE (6,2900) D
      CALL PLOTP(PT,POUT,KK,0)
      GG=TIME(1)*TIMES
      B=TIME(1)+TIME(III)
      C=(B/2)*TIMES
      A=(TIME(III)-TIME(1))*TIMES
      WRITE (6,2200) C,A,GG
 2200 FORMAT(//T30,'THE TIME OF OCCURANCE OF THE CENTER OF THE MAIN ',
     1'LOBE IS',F8.2,'.',//,T30,'THE WIDTH OF THE MAIN LOBE IS',
     2 F8.2,'.',//,T30,'THE LEADING EDGE OF THE MAIN LOBE OCCURS ',
     3'AT',F8.2,'.',/)
   67 WRITE (6,2300)
```

```
 2300 FORMAT (//'*******Y*******************************************',
     1'************************************************Y************',/)
C
C     INCREMENT THE ANGLE BY DELDEG
C
C
      ANGLE=ANGLE+DELDEG
      IF (ANGLE.LE.STOP) GO TO 2
      IF (JJJJ.EQ.2) GO TO 3600
      WRITE (6,3000) GO,AAAA
 3000 FORMAT(//T30,'THE ANGLE OF ARRIVAL OF THE SIGNAL IS PLOTTED',/
     1T30,'ALONG THE X-AXIS IN DEGREES AND THE MAXIMUN AMPLITUDE OF',/
     2T30,'THE FILTER OUTPUT IS PLOTTED ALONG THE Y-AXIS',/
     3T30,'...DISREGARD THE VALUES',F4.1,'/0.0 AND 90.0/',F4.1,'THEY'/
     4T30,'ARE DUMMY VALUES USED TO SCALE THE PLOT',//)
      NX=IC
      WRITE (6,2900) D
 2900 FORMAT (////T30,'THE FILTER DELAY=',F5.3,' TIMES THE ANTENNA ',
     1 'SEPARATION',//)
      WRITE (6,3100)
 3100 FORMAT (//T30,'ANGLE OF ARRIVAL',//)
      WRITE (6,3200) (TA(I),I=1,NX)
 3200 FORMAT (' ',T20,10F7.1,/)
      WRITE (6,3300)
 3300 FORMAT (//T30,'MAXIMUM FILTER OUTPUT',//)
      WRITE (6,3400) (TOUT(I),I=1,NX)
 3400 FORMAT (' ',T20,10F7.1,/)
      IC=IC+1
      TA(IC)=0
      TOUT(IC)=0.0
      IC=IC+1
      TA(IC)=90.0
      TOUT(IC)=AAAA
      WRITE (6,3500)
 3500 FORMAT ('0','0',/)
      CALL PLOTP(TA,TOUT,IC,0)
C
C
C     INCREMENT THE FILTER DELAY BY DSTEP
C
C
 3600 D=D+DSTEP
      IF (D.LE.1.00) GO TO 1
      GO TO 6000
 4000 WRITE(6,5000)
 5000 FORMAT(///T20,'DATA EXCEEDS ARRAY STORAGE...JOB TERMINATED',///)
 6000 STOP
      END
```

```
      FUNCTION F(T,I,W,DELAY,TIMES)
      INTEGER*4 T3,FIL3,DELT3,W3,D3
      T1=T
      T2=TIMES*T1+0.1
      T3=IFIX(T2)
      W1=W
      W2=TIMES*W1+0.1
      W3=IFIX(W2)
      D1=DELAY
      D2=TIMES*D1+0.1
      D3=IFIX(D2)
      F=0.0
      IF(T3.LT.((I-1)*D3)) GO TO 190
      F=1.0
      IF(T3.LE.(((I-1)*D3)+W3)) GO TO 190
      F=0.0
  190 RETURN
      END


      FUNCTION G(T,J,FILTER,DELT,M,TIMES)
      COMMON/ZZZ/ADD(2000)
      COMMON/AAA/ADD1(2000)
      COMMON/BBB/ADD2(2000)
      INTEGER*4 T3,FIL3,DELT3,W3,D3
      T1=T
      T2=TIMES*T1+0.1
      T3=IFIX(T2)
      FIL1=FILTER
      FIL2=TIMES*FIL1+0.1
      FIL3=IFIX(FIL2)
      DELT1=DELT
      DELT2=TIMES*DELT1+0.1
      DELT3=IFIX(DELT2)
      G=0.0
      IF(T3.LT.((J-1)*FIL3)) GO TO 290
      KKK=((T3-((J-1)*FIL3))/DELT3)+1
      IF (M.GT.1) GO TO 291
      G=ADD1(KKK)
      GO TO 290
  291 G=ADD2(KKK)
  290 RETURN
      END
```

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13. ABSTRACT

Unambiguous accurate direction finding results are obtained by the use of large stationary antenna systems at the lower frequencies and by the use of rotatable antennas at the higher frequencies. While these techniques result in good data they suffer from the fact that accuracy is generally a direct function of the antenna size, that is, accuracy increases as the antenna size increases.

A system is proposed which encodes the outputs of several simple omnidirectional antennas and processes this modified signal to provide angle-of-arrival data. The processor not only provides the angle-of-arrival data but the received signal is preserved as a simultaneous output with the bearing data.

The coding is accomplished utilizing complementary sequences and a derivative of these sequences called orthogonal complementary sequences. The technique is described in detail and a digital computer model was developed to support the theory.

KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Direction Finding						
Complementary Series						
Complementary Codes						
Golay Codes						
Phase Coding						